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# CHARACTERIZATION OF HEAT TRANSFER IN CERAMIC COATED INTERNAL COMBUSTION ENGINES

FINAL REPORT REPORT ONE

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4. Discuss the results of an endurance test of ceramic coated engine parts.

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#### INTRODUCTION

The following document is a final report for Grant Number DAAG29-79-G-0021 funded by the U.S. Army Research Office. This project was started 1 January 1979 and had a duration of two years.

In general, the project was 1) to develop a mathematical model describing heat transfer and temperature characteristics in ceramic coated engine components, 2) measure operational temperatures for such parts with various coating thickness, and 3) continue a previous endurance test of ceramic parts.

## THEORETICAL BACKGROUND

#### **PURPOSE**

Since the time of Rudolph Diesel, engineers have been trying to develop engines that waste less energy, and thereby develop more power with a given quantity of fuel. It is widely accepted that heat transferred to the cooling system of an engine represents wasted energy. On the other hand, the only practical way known to control engine temperatures is to provide such cooling. In reciprocating engines, the design of pistons and valves has always required careful consideration of temperature as related to component strength and to lubrication. But the cooling necessary to keep these components from overheating not only reduces engine power production, but consumes power to drive the cooling mechanism.

It was recognized by the author that an insulating surface on combustion chamber surfaces offered an approach to the cooling problem by reducing heat transfer to the cooling system and, at the same time, provided lower temperatures of metallic components. Lower metallic temperatures allow redesigning of components for less weight and lower frictional drag.

From a design standpoint, therefore, lower piston temperatures enable lower piston weight, which leads to reduced inertia loadings thus allowing smaller and lighter components such as crankshaft bearings, connecting rods, and crankcase structure. The lower temperatures also allow a new freedom in selecting lubricating oils that can reduce viscous drag and windage losses within the crankcase.

A second significant benefit that may result from ceramic coatings is the reduction of the failure rate in valves and pistons, and therefore an increase in engine reliability. While replacement costs for individual engine parts are not unreasonable, the time of failure and the labor required are often critical factors in vulnerable situations.

Engine failure is particularly critical in military applications. Often military engines are destroyed by a combination of operational factors in or near a combat zone. For example, it is not uncommon for the operator to refuel with any available fuel and then operate the vehicle at peak power for extended time intervals. Either a spark ignition (S-I) or a compression ignition (C-I) engine operated in this mode will develop severe knock. Knock, in turn, dramatically increases convection boundary layer heat transfer which may raise valve and piston temperature to a point of failure.

Figure 1, following, is a photograph illustrating a diesel exhaust valve failure caused by excessive thermal stress (hoop stress failure). A more common failure occurs when the valve head separates from the stem ("valve swallowing"), after high temperature stress and erosion. This second failure mode usually occurs at high power and high rpm conditions resulting in substantial, if not complete, engine destruction.

Two examples of piston damage resulting from high temperature operation are shown in figures 2 and 3. Both are caused by knock induced heat transfer. The second, however, was aggravated by preignition at the spark plug center electrode.

Insulated coatings are expected not only to economically eliminate all of the above types of engine failure, but also, to increase engine efficiency and reduce overall engine weight.

Based on the information above, it appears that one small breakthrough in controlling heat transfer offers the opportunity for major engine improvement. For these reasons, it is highly desirable to gain a better



Figure 1: Valve Failure



Figure 2: Piston Failure Knock



Figure 3: Piston Failure Preignition

understanding of how heat is transferred in ceramic coated internal combustion engine parts.

#### PREVIOUS WORK

Shortly after the principal investigator realized the possible benefits of insulated combustion chamber surfaces, he wrote a mathematical model to investigate coated engine performance. The model did predict both increased efficiency and lower component temperatures. Following analysis of the model, he participated in two engine test programs involving coated parts.

The first engine test program was a multicylinder test at the Johnson Space Center in Houston. The major outcome of this test was proof that plasma sprayed ceramic coatings could endure the torturous environment of an engine combustion chamber for extensive periods of time without significant deterioration.

The second test program was a U.S. Army funded study at Oklahoma State University which investigated engine performance characteristics. Both spark ignition (S-I) and compression ignition (C-I) performance were investigated at various compression and equivalence ratios. These tests incorporate a thin coating (0.025") of yttrium stabilized zirconium oxide on the piston, valves, and cylinder head surfaces of a Cooperative Fuel Research (CFR) engine. In addition, tests were undertaken to investigate how various catalysts applied to these coatings will affect combustion. The details of this project are found in the final report, project No. P-14099-E entitled "Improved Engine Performance Through Heat Transfer Control", available by contacting the U.S. Army Research Office, Research Triangle, North Carolina.

#### CERAMIC COATINGS

Several ceramic substances have been developed in the last few years that exhibit excellent insulating properties. These substances can be sprayed on metal surfaces by flame or plasma methods and also can be applied by a device known as a detonation gun. Some properties of various

coatings and metals follow in table 1.

To reduce heat transfer in an engine cylinder, two physical coating properties are of prime importance. First, the material must adhere to the metallic subsurface without any significant interface stress over a wide range of temperature. This necessitates that the coefficient of thermal expansion of the coating should be of the same order of magnitude as the base structure. Second, it should have as low a thermal conductivity as possible in order to effectively control heat transfer. Properties of lesser importance are specific heat, compressive strength, and adherence. Of all the coating materials investigated, yttrium stabilized zirconium oxide best fits the requirements for engine combustion chamber insulation.

Adherence of plasma and flame sprayed zirconium oxide to cast iron and aluminum surfaces is, however, in some cases not good, and coating separations will occur if proper techniques are not observed. Metallic surfaces must be clean and free of oil prior to coating. In some cases, it may be necessary to preheat cast iron surfaces to expel residual oil from machining process. To promote good bonding, it is suggested that metallic surfaces be grit blasted and given a flash coat of nickel aluminate before application of the zirconium oxide coating.

#### PROJECT SCOPE

The preceding section has outlined the historical use of ceramic coatings to improve engine performance and to make engines more tolerant of low grade fuel. This project was undertaken to establish a data base to assist design engineers in the adoption of ceramic coatings. To achieve this goal, a two year project was implemented to:

- 1) create a mathematical model that can predict piston and exhaust valve heat transfer as a function of engine design parameters and coating characteristics,
- 2) establish operational temperature profiles for coated pistons and valves, and
- 3) an additional assignment for this project was to

Table 1
PHYSICAL PROPERTIES

Material	Thermal Conductivity	Coefficient of Expansion	Bulk Density	Specific Heat	Melting Temperature
	BTU hr ft °F	in °Fx 10 <sup>-6</sup>	gm cm <sup>3</sup>	BTU # °F	°F
	$(\frac{\text{cal}}{\text{Sec cm C}})$	$\left(\frac{\text{cm}}{\text{cm C}} \times 10^{-6}\right)$		$(\frac{\operatorname{cal}}{\operatorname{cm} C})$	(°C)
Zirconium Oxide	0.67 (2.77 x 10 <sup>-3</sup> )	5.4 (3.0)	5.2	0.175 (6.018)	4500 (2482)
Aluminum Oxide	1.58 (0.01)	4.1 (2.28)	3.3	0.28 (0.028)	3600 (1982)
Chrome Oxide	1.50 (0.01)	5.0 (2.78)	4.6	0.20 (0.020)	3000 (1649)
Aluminum	120 (0.50)	13.0 (7.22)	2.7	0.22 (0.022)	1220 (660)
Cast iron	27 (0.11)	6.5 (3.61)	7.88	0.11 (0.011)	2800 (1538)

Source:"Rokide Ceramic Spray Coating", The Norton Company, 1961. continue an endurance test for ceramic coated engine parts. Prior to the start of this project an engine had undergone 1000 hours of operation simulating highway conditions. A second 1000 hours of operation was established as a third goal of this project.

#### THE MATHEMATICAL MODEL

#### GENERAL

Engine pistons and exhaust valves are three dimensional objects having configurations that can typically be portrayed by figures 4 and 5, respectively.

The piston and valve combustion chamber surfaces receive a cyclic heat input during each combustion, expansion and exhaust process. This heat flow depends primarily on the power loading of the engine and the combustion characteristics. These same surfaces are also subjected to a cyclic cooling during the intake and compression processes. The cooling tendency varies mainly with air-fuel ratio and engine power level.

Primary piston cooling is through the piston rings and heat transfer to lubricating oil, both being somewhat cyclic in nature.

Exhaust valve heat rejection occurs primarily to the valve seat and valve guide. Both of these sinks change characteristics with time and therefore are transient in nature.

While both the piston and exhaust valve are transient heat transfer devices, they may be treated as steady state for practical purposes. The insulating effect of a ceramic surface tends to isolate the core metal structure from temperature fluctuations, in other words, it is believed that the interior temperature of both such pistons and valves is controlled more by the constant temperature sink and the physical properties of the metal than by the cyclic heat load. This theory was verified in the laboratory; details and test data confirming this will be presented later.

As seen in figure 5, the exhaust valve is symmetrical and can, therefore, be treated as a two dimensional heat transfer body.

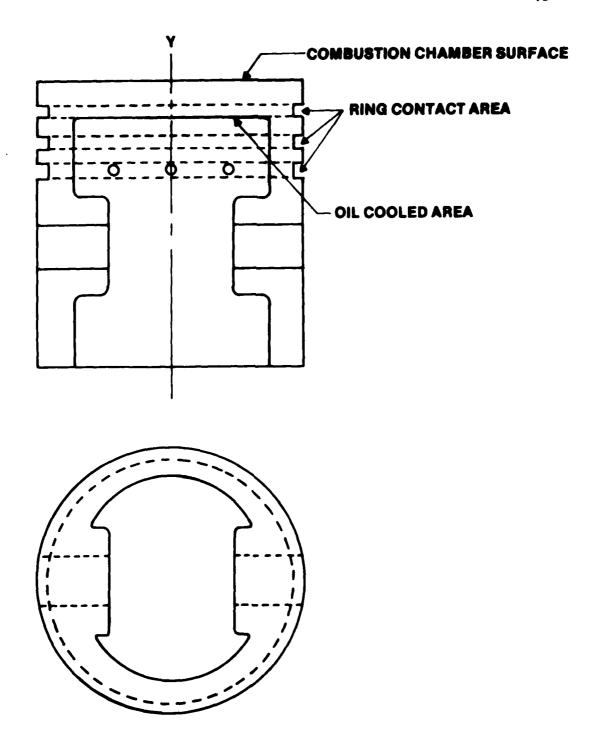


Figure 4: Typical Piston Configuration

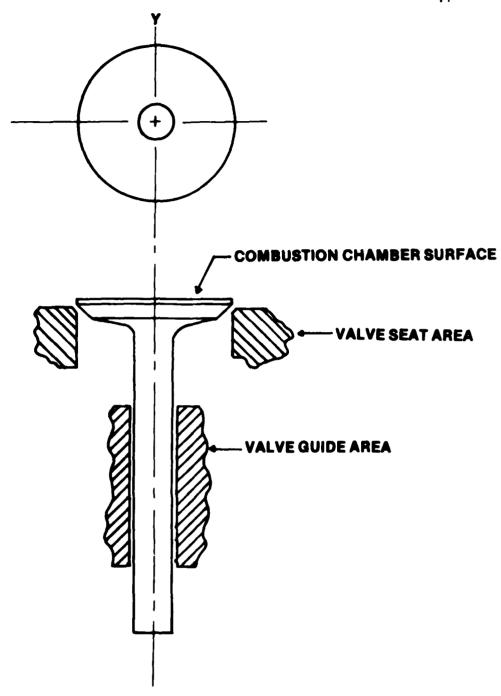


Figure 5: Typical Valve Configuration

The piston is also basically symmetrical with the exception of the wrist pin boss. This boss, however, is typically located well below the ring area and, therefore, is usually considered to have little contribution to the overall piston heat transfer. Studies indicate that most heat transfer takes place in the upper ring area and on the top portion of oil cooled lower piston crown (1-7)\* and, therefore, confirm that the wrist pin boss may be treated as an insignificant factor in heat transfer. This reasoning allows one to treat piston and valve heat transfer as a two dimensional, steady state problem.

If one first examines the general relationships for three dimensional heat transfer in an element as shown in figure 6, he can determine the heat transfer (8) in each of the three directions from

$$q_{X} = -KA \left( \frac{\partial}{\partial X} \right) \tag{1}$$

where A = dy dx,

$$q_y = -KA \left( \frac{\partial T}{\partial y} \right) \tag{2}$$

where A = dx dz,

and

$$q_z = -KA \left( \frac{\partial T}{\partial z} \right) \tag{3}$$

where A = dx dy,

where T is temperature, K is thermal conductivity, and q is heat transfer. The three dimensional heat conduction equation for homogeneous materials without interior heat generation is:

<sup>\*</sup>References are at the end of narrative.

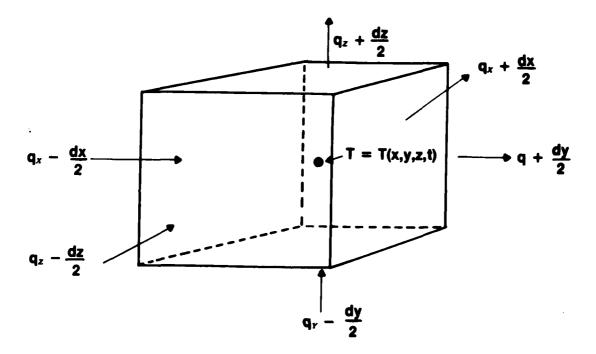


Figure 6: Elemental Heat Transfer

$$\frac{\partial T}{\partial t} = K \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) , \qquad (4)$$

where t is time.

For steady state conditions  $\frac{\partial T}{\partial t} = 0$  and equation 4 becomes

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0.$$
 (5)

The above is known as Laplace's Equation and is often written as  $\triangle T = 0$ . If Laplace's Equation is transformed to cylindrical coordinates by substituting  $x = r \cos \Theta$ ;  $y = r \sin \Theta$ ; and z = z; and if cylindrical symmetry is assumed

$$(\frac{\partial T}{\partial \Theta} = 0),$$

the equation reduces to:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = 0 . \tag{6}$$

Since symmetry is justified in this study, equation 6 becomes the governing equation for pistons and exhaust valves. Figure 7 illustrates this application for a piston.

To solve the heat transfer problem for such components, one must solve Laplace's Equation having certain boundary conditions known. A finite difference approach to this solution has been selected and will follow.

#### FINITE DIFFERENCE METHOD

Laplace's Equation has a unique solution for each set of boundary conditions specified. However, analytical solutions have been worked out only for problems with certain special geometries and boundary conditions. The following solution will be to overlay the cross section of the piston (and valve) with a grid of points (r, z) and to

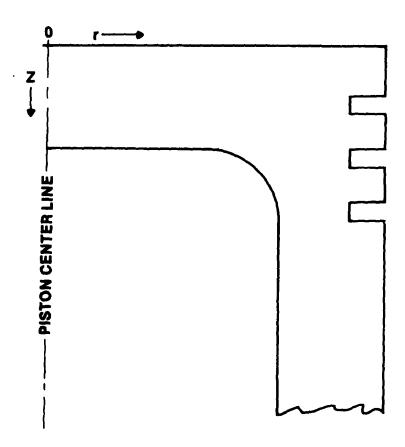


Figure 7: Piston Cross Section

find the temperature at each point numerically. A typical grid is as follows in figure 8.

The numerical approach first approximates the partial derivatives at each point by using a finite difference or

$$\frac{\partial T}{\partial r}(r,z) \doteq \frac{1}{2h_1} \left[ T_{(r+h_1,z)} - T_{(r-h_1,z)} \right] \tag{7}$$

$$\frac{\partial^2 T}{\partial r^2} (r,z) \doteq \frac{1}{h_1^2} \left[ T(r + h_1,z) + T(r - h_1,z) - 2T_{(r,z)} \right]$$
 (8)

and

$$\frac{\partial^2 T}{\partial z^2} (r,z) = \frac{1}{h_2^2} \left[ T_{(r,z+h_2)} + T_{(r,z-h_2)} - 2T_{(r,z)} \right]$$
 (9)

where  $\mathbf{h}_1$  is the horizontal grid spacing and  $\mathbf{h}_2$  is the vertical grid spacing.

Equation 6 now becomes:

$$\frac{1}{h_1^2} \left[ T(r + h_1, z) + T(r - h_1, z) - 2T(r, z) \right] + \frac{1}{rh_1} \left[ T(r + h_1, z) - T(r - h_1, z) \right] +$$

$$\frac{1}{h_2^2} \left[ T(r,z+h_2) + T(r,z-h_2) - 2T(r,z) \right] \doteq 0. \tag{10}$$

For the center line element (r = 0) a slightly different approximation is needed. As

$$r \to 0$$
,  $\frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}$ 

so the governing equation becomes:

$$2\frac{J^{2}T}{Jr^{2}} + \frac{J^{2}T}{Jz^{2}} = 0. {(11)}$$

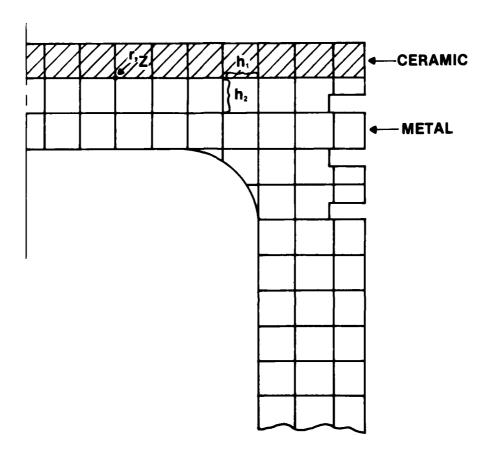


Figure 8: Piston Grid Network

The above can be simplified if  $h_1 = h_2$  and the following substitutions are made:

$$T(r + h,z) = T_{i} + 1, j$$

$$T(r - h, z) = T_{i} - 1, j$$

$$T(r, z + h) = T_{i}, j + 1$$

The following finite difference equations exist for all points except where r = 0:

$$0 = -4 T_{i,j} + T_{i,j} + 1 + T_{i,j-1} + (1 - \frac{h}{2r}) T_{i-1,j} + (1 + \frac{h}{2r}) T_{i+1,j}$$

$$(1 + \frac{h}{2r}) T_{i+1,j}$$

$$(12)$$

For center line points, (r = 0), the corresponding finite difference equation is:

$$0 = -6 T_{i,j} + 2T_{i-1,j} + 2T_{i+1,j} + T_{i,j+1} + T_{i,j-1}$$
 (13)

which by symmetry yields:

$$0 = -6 T_{i,j} + 4 T_{i+1,j} + T_{i,j+1} + T_{i,j-1}$$
 (14)

#### MODELING THE CERAMIC COATING

Special consideration must be given to the points where the ceramic coating meet the metallic piston (valve) surface. Linear equations for these points are obtained by assuming a one dimensional flow across the ceramic and using the heat equation:

$$q = -KA \frac{\partial T}{\partial z} . (15)$$

This is illustrated in figure 9.

To obtain an equation involving  $T_1$ ,  $T_2$ , and  $T_3$  one can calculate the heat flowing through the interface area (A) both from the ceramic and the metal.

$$q = -K_c A \left( \frac{T_1 - T_2}{d} \right)$$
 (16)

and

$$q = -K_m A \left( \frac{T_2 - T_3}{h_2} \right)$$
 (17)

Equating these equations yields:

$$\frac{K_c^A}{d} (T_1 - T_2) = \frac{K_m^A}{h_2} (T_2 - T_3)$$
 (18)

or

$$T_2 = \frac{h_2 K_c T_1 + d K_m T_3}{h_2 K_c + d K_m}$$
 (19)

This gives a linear equation for each grid point of contact from the ceramic and the metal.

#### COMBINED SOLUTION

An equation now exists for the temperature at each interior point (r,z) and the surrounding grid points. The n-equations involving nunknowns have been generated. These equations can be solved directly by Gaussian elimination or by an iterative process like the Gauss-Seidel method. In the Gauss-Seidel method the temperature at one point (r,z) is solved in terms of the temperatures at all surrounding grid points.

The result is a temperature distribution throughout the piston or valve.

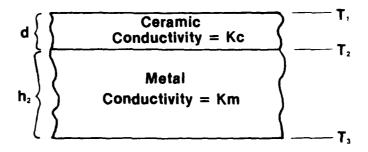


Figure 9: Ceramic Metal Interface

#### DETERMINATION OF THERMAL CONDUCTIVITY

The thermal conductivity of each substance involved must be accurately known over a range of temperatures before any mathematical model can be completed. The temperature dependency of aluminum, steel, cast iron and other metals is well known and documented over a reasonable range. Plasma sprayed zirconium oxide, however, does not have a widely accepted conductivity at the temperatures involved by engine components.

Before completion of a mathematical model, therefore, it was necessary to determine such values. Samples of steel were machined to a standard sample size. Several of these were plasma sprayed with yttrium stabilized zirconium oxide using the same techniques as for engine parts. These samples, as well as uncoated specimens, were sent to the Thermophysical Properties Research Laboratory at Purdue University for evaluation. The results of this analysis were incorporated in the following computer model and are presented as appendix 1.

#### THE COMPUTER PROGRAM

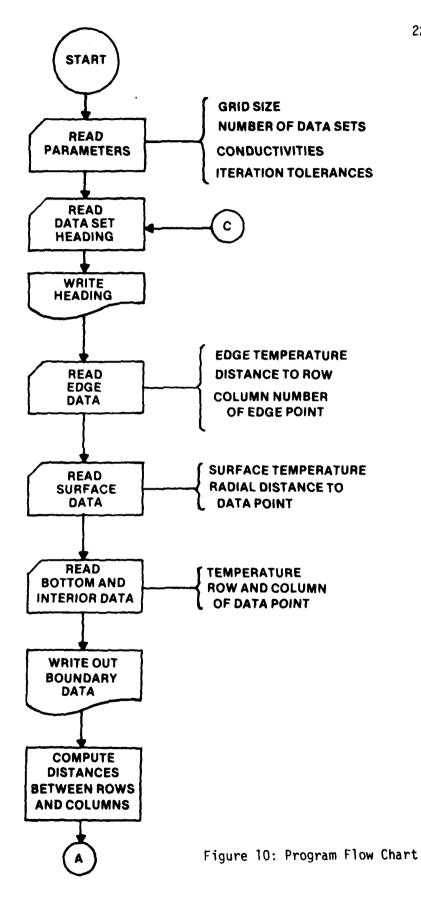
The preceding section has illustrated a mathematical method to describe the temperature at all interior points for engine parts that encounter two dimensional (r,z), steady state heat transfer.

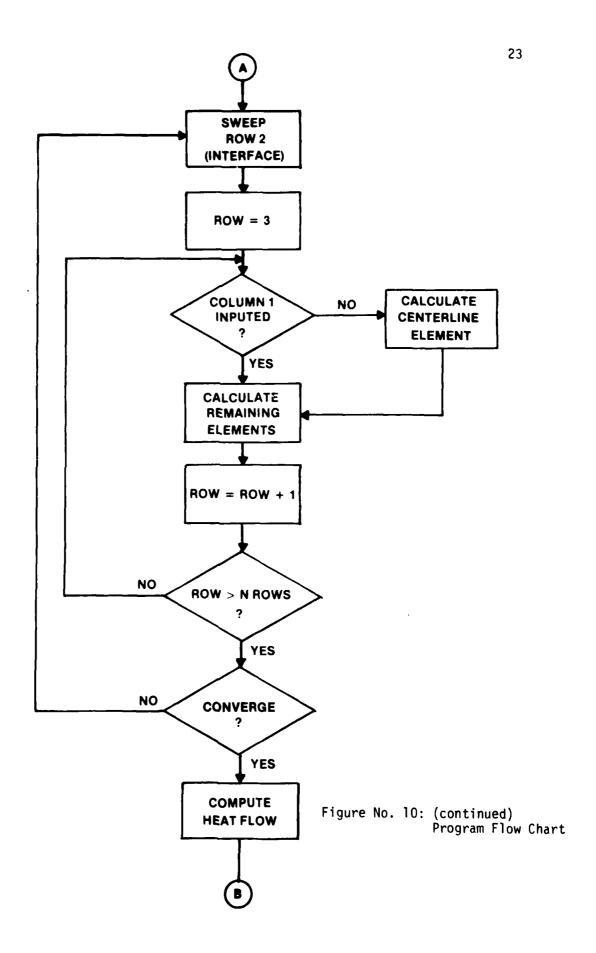
A major portion of this effort was to incorporate these equations into a computer program that would give engineers a tool for designing engines that incorporate ceramic coated pistons and valves. The following section outlines the details of the resulting program.

Figure 10 details the step by step procedure to input component details into the program and to acquire the resulting temperature profiles and heat transfer.

To implement the program, a grid must be established similar to the one following in figure 11. The temperature at each solid dot is needed in the data.

The first data card contains the number of rows, the number of columns, the number of data sets, the conductivity of the coating, the conductivity of the metal, and the acceptable iteration limit. A data





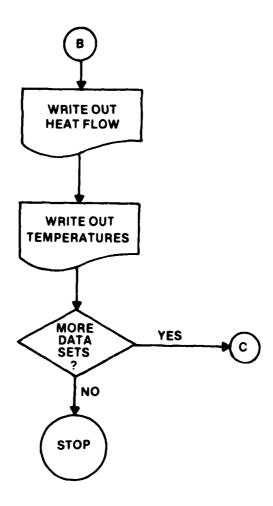


Figure No. 10: (continued)

Program Flow Chart

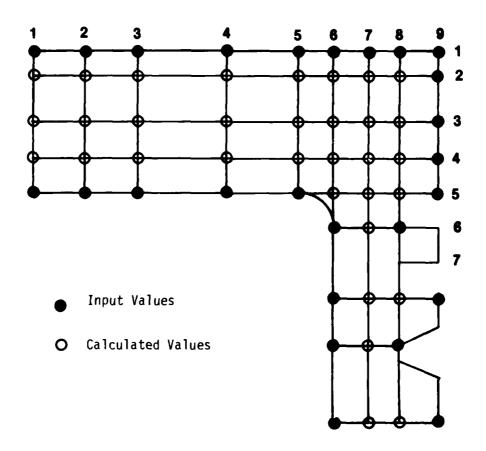


Figure 11: Piston Grid Points

set consists of the boundary temperatures for the test of a particular configuration. This information applies to all the data sets that follow. Each data set is composed of four sections. The first section is a single card which contains the label for the data set. The second section contains the temperatures along the outer edge. For each row there is one card which contains the edge temperature, and the dimensions to the point from the top and perimeter of the component by column number. The vertical dimension is recorded in inches of depth while the horizontal dimension is stated only by column number. The format for these cards is (F10.3, F9.3, I2). The temperature is recorded in degrees Fahrenheit (in agreement with the units on thermal conductivity) and the distance is recorded in inches.

The third section of the data set is composed of the surface temperatures and column spacing. For each column in the grid, a surface temperature and distance from the center of the piston valve is given. The format is (2F10.3). Again, the temperature is in degrees Fahrenheit and the radial location is recorded in inches.

The last section of the boundary data contains the temperatures on the bottom and interior wall (crankcase surface) for the piston and for the tulip on the valve. Each data card in this section contains a row, column, and temperature of a boundary point not covered in either section two or three.

A data card of this type with row = 20 and column = 20 is needed to signal the end of the data for each set. The format for these cards is (215,F10.3).

Note that the distance between rows 1 & 2 corresponds to the coating thickness. As written, this program solves for 9 rows and 9 columns. This quantity can be increased by changing the format and programming for the last data card of the fourth data section.

The output of this program contains a representation of the boundary values inputed into the program, a final temperature for each grid point, and the rate of heat flow vertically from the surface of the piston (or valve) in BTU/hr.

A card by card listing of the final version of the program follows:

(see next page)

A sample set of data cards used to test the program is listed below:

(see following pages)

These data cards produce an output as follows:

(see following pages, table 4-Program Output).

The following is a series of two profiles, each of which roughly outlines the geometry of the part being tested. The top profile tabulates inputed temperatures and the respective location of each point. The top outside points has values of r=1.63 inches, z=0.00 inches and  $t=280\ ^{\circ}F$ . Interior points are unknown at the time of data input and are therefore printed as zero.

The calculated heat flow through the top surface is written between the two profiles and in this sample case equals 366.7 BTU per hour.

The second (lower) profile displays the calculated temperatures at interior points as well as the input data from the top profile. In both profiles, the area shaded by the letter "U" represents the crankcase environment.

The program gives one the ability to calculate heat flow and the temperature and distribution for any coated engine part with two dimensional heat flow.

#### **OPERATIONAL TEMPERATURES**

#### **GENERAL**

To design engines incorporating ceramic coated parts, it is desirable not only to have a mathematical model that calculates heat flow and interior temperatures, but also one needs information about actual surface temperatures as they relate to engine operating conditions. In addition

AAJOR VARIBLES USED  SUP(1, J) - TEMPERATURE AT GRIC FGINT 1, J.  RONS - NUMBER OF FOUS IN GRID.  COLS - NUMBER OF COLUMNS IN GRID.  KINSU - CONDUCTIVITY OF THE METAL.  VGTCL - ALLOMABLE AVERACE TEMPERATURE CHANGE  RID - CONDUCTIVITY OF THE NETAL.  VGTCL - ALLOMABLE TEMPERATURE CHANGE AT ANY  EDGE(1) - TEMPERATURE ON THE EDGE AT ROW 1.  DIST(1) - VERTICAL DISTANCE TO ROW 1.  COLUMN NUMBER OF FIRST CALCULATED GRID  FIXED - DISTANCE BETWEEN COLUMNS I AND 1+1.  FIXED - OISTANCE BETWEEN COLUMNS IN GRID.  - VERTICAL RATE OF HEAT FLCW.	DF A VALVE SUBSTANCE TEMPERATUR OETERMINED	DF A VALVE (SUESTANCE SUETEMPERATURE)	SUCE AS	VALVE OR DISTON COATED WITH AN INSULATING ANCE SUCH AS A CERANIC MATERIAL. THE RATURE AT THE INTERICR GFID POINTS IS ALSO MINED.	AR000004 AR000006 AR0000006 AR000000
TEMP(1, J) - TEMPERATURE AT GRID FOINT 1, J,  COLS - NUMBER OF COLUMNS IN GRID.  CUNS - NUMBER OF COLUMNS IN GRID.  CINSU - CONDUCTIVITY OF THE METAL.  CANDUCTIVITY OF THE METAL.  CALOUABLE AVERAGE TEMPERATURE CHANGE IN DEGREES F BETWEEN ITERATIONS.  AXTOL - ALLOWABLE TEMPERATURE CHANGE AT ANY GRID POINT PER ITERATION.  EDGE(1) - TEMPERATURE ON THE EDGE AT ROW I.  DIST(1) - VERTICAL DISTANCE TO ROW I.  Z(1) - OISTANCE EETWEEN COLUMNS I AND I+1.  FIRST(1) - OISTANCE EETWEEN COLUMNS I AND I+1.  FIRST(1) - OISTANCE EETWEEN COLUMNS I AND I+1.  FIRST(1) - OISTANCE EETWEEN COLUMNS I NO I+1.  FIRST(1) - OISTANCE EETWEEN COLUMNS IN GRID.  FIXED - NUMBER OF FOINTS IN ROW I THAT ARE NOT CCWPUTED POINTS IN GRID.  - VERTICAL RATE OF HEAT FLOW.  TEMP.ROIST.ZDIST.ABSDIF.OIFSUW.OMEGA.DIFMAX  ST.NORS.MOLIS.JFIRST HEAGLED.  TEMPROS.ZDIST.ABSDIF.OIFSUW.OMEGA.DIFMAX  TEMPROS.ZDIST.ABSDIF.OIFSUW.OMEGA.DIFMAX  TEMPROS.ZDIST.ABSDIF.OIFSUW.OMEGA.DIFMAX  TEMPROS.ZDIST.ABSDIF.OIFSUW.OMEGA.DIFMAX  TEMPROS.ZDIST.ABSDIF.OIFSUW.OMEGA.DIFMAX  TEMPROS.ZDIST.ABSDIF.OIFSUW.OMEGA.DIFMAX  TEMPROS.ZDIST.ABSDIF.OIFSUW.OMEGA.DIFMAX  TEMPROS.ZDIST.ABSDIF.OIFRITIZO). MFIXEDIZO)  DOICTOR TO THE RELAXATION.  TEMPROS.ZDIST.ABSDIF.OIFSUW.OMEGA.DIFMAX  TEMPR		7	F0. €1	VAR IABLES	ARO000010 ARO000010 ARO00020
COLS - NUMBER OF COLUMNS IN GRID.  CUNS - NUMBER OF COLUMNS IN GRID.  CINSU - CONDUCTIVITY OF THE METAL.  CONDUCTIVITY OF THE METAL.  GRID POLYTY OF THE METAL.  ALLOWABLE AVERAGE TEMPERATURE CHANGE IN DEGREES F BETAEEN ITERATIONS.  AXTOL - ALLOWABLE TEMPERATURE CHANGE IN DEGREES F BETAEEN ITERATIONS.  EDGE(1) - TEMPERATURE ON THE EDGE AT ROW I.  DIST(1) - VERTICAL DISTANCE TO ROW I.  DIST(1) - VERTICAL DISTANCE TO COLUMN I.  FIRST(1) - OISTANCE ETWEEN COLUMNS I AND I+1.  FIRST(1) - OISTANCE RADE OF FIRST CALCULATED GRID  POINT IN FOW I.  FIRST - NUMBER OF POINTS IN ROW I THAT ARE NOT  COMPUTED.  - VERTICAL RATE OF MEAT FLOW.  - VERTICAL RATE	TEMP(	1. 11	,	AT GRIC FOINT	AR000030 AR000040
TUNS - NUMBER OF COLUMNS IN GRID.  CLINSU - CONDUCTIVITY OF THE WETAL.  GETCL - ALLOWABLE NYBRAGE TEMPERATURE CHANGE  GRID POINT PER ITEMATION.  EDGE(I) - TEMPERATURE CHANGE AT ANY  GRID POINT PER ITEMATION.  DIST(I) - VERTICAL DISTANCE TO ROW I.  Z(I) - OISTANCE EFFER RCW I AND ROW I+1.  FIRST(I) - OISTANCE EFFER RCW I.  FIRST(I) - OISTANCE EFFER RCW I AND ROW I+1.  FIRST(I) - OISTANCE EFFER RCW I AND ROW I+1.  FIRST(I) - OISTANCE EFFER RCW I.  FIRST(I) - OISTANCE EFFER RCW I AND ROW I+1.  FIRST(I) - OISTANCE EFFER RCW I AND ROW I+1.  FIRST(I) - OISTANCE EFFER RCW I AND ROW I+1.  FIRST(I) - OISTANCE EFFER RCW I AND ROW I+1.  FIRST(I) - OISTANCE EFFER RCW I AND ROW I+1.  FIRST(I) - OISTANCE EFFER RCW I AND ROW I+1.  FIRST(I) - OISTANCE EFFER RCW I AND ROW I+1.  FIRST(I) - OISTANCE EFFER RCW I AND ROW I+1.  FIRST(I) - OISTANCE EFFER RCW I AND ROW I+1.  FIRST(I) - OISTANCE EFFER RCW I	SHORK		ı	P FOWS IN	AR000056
CHINSU - NUMBER OF DATA SETS TO BE RUNG.  CHASU - CONDUCTIVITY OF THE COATING.  CHETL - CCNOUCTIVITY OF THE METAL.  CHOUCTIVITY OF THE METAL.  ALLOWABLE TEMPERATURE CHANGE AT ANY GRID POINT PER ITEMATIONS.  MATOL - ALLOWABLE TEMPERATURE CHANGE AT ANY GRID POINT PER ITEMATION.  DIST(I) - VERTICAL DISTANCE TO ROW I.  DIST(I) - VERTICAL DISTANCE TO ROW I.  Z(I) - CISTANCE EETWEEN COLUMN I.  Z(II) - CI	NCOLS	•-	1	OF COLUMNS IN GRID	AR000060
CINSU - CONDUCTIVITY OF THE COATING.  CHETL - CENDUCTIVITY OF THE METAL.  CHETL - CENDUCTIVITY OF THE METAL.  CHETL - CENDUCTIVITY OF THE METAL.  ALCUMBLE FURBAGE TEMPERATURE CHANGE AT ANY GRID POINT PER ITERATION.  EDGE(I) - TEMPERATURE ON THE EDGE AT ANY GRID POINT PER ITERATION.  ELISTANCE FROM CENTER TO COLUMN I.  EISTANCE EFFUEEN RCW I AND I+1.  FIRST(I) - DISTANCE EFFUEEN COLUMNS I AND I+1.  FIRST(I) - OISTANCE EFFUEEN COLUMNS I AND I+1.  FIRST(I) - OISTANCE EFFUEEN COLUMNS I AND I+1.  FIRST(I) - OISTANCE EFFUEEN COLUMNS I AND I+1.  FIRST OCCUMN MUMBER OF FIRST CALCULATED GRID POINT IN FOW I THAT ARE NOT COMPUTED.  HPTS - NUMBER OF COMPUTED POINTS IN GRID.  - VERTICAL RATE OF HEAT FLOW.  TEMPS - ACCELERATION CONSTANT IN THE RELAXATION.  (FIXED AT 1.5)  TEMPS - ACCELERATION CONSTANT IN THE RELAXATION.  (FIXED AT 1.5)  TEMPS - ACCELERATION DISSICADI. LAST(20)  TEMPS - ACCELERATION JFIRST(20). NFIXED(20)  1000  1000	· Carlo	_			AR060100
CINSU CONDUCTIVITY OF THE COATING.  CMETL CCNOUCTIVITY OF THE NETAL.  ALLOWABLE NERAGE TEMPERATURE CHANGE IN DEGREES F BETWEEN ITERATIONS.  AXTOL ALLOWABLE TEMPERATURE CHANGE AT ANY GRID POINT PER ITERATION.  DIST(I) TEMPERATURE ON THE EDGE AT ROW I.  DIST(I) VERTICAL DISTANCE TO ROW I.  Z(I) CISTANCE FERM CENTER TO COLUMN I.  FIRST(I) CISTANCE EFTWEEN COLUMNS I AND I+1.  FIRST(I) COLUMN NUMBER OF FIRST CALCULATED GRID POINT IN FCW I.  FIXED NUMBER OF POINTS IN ROW I THAT ARE NOT  CCWPUTED.  VERTICAL RATE OF HEAT FLOW.  TEMPORALS. JEIRST  HEAD(20)  TEMPORALS. JEIRST  HEAD(20)  TEMPORALS. JEIRST  HEAD(20)  TEMPORALS. JEIRST  HEAD(20)  DEGREES AT 1.5)  TEMPORALS. JEIRST  HEAD(20)  DEGREEOUS JEIRST  JENST(20) NEIXED(20)	N COL	_	,	UP DATA SETS TO BE	ARC00110 ARC00120
TEMP. ALCUMBLE AVERAGE TEMPERATURE CHANGE IN DEGREES F BETWEEN ITERATIONS.  AXTOL - ALLOWABLE TEMPERATURE CHANGE AT ANY GRID POINT PER ITERATION.  EDGE(I) - TEMPERATURE ON THE EDGE AT ROW I.  DIST(II) - VERTICAL DISTANCE TO ROW I.  Z(II) - OISTANCE FROM CENTER TO COLUMN I.  Z(II) - OISTANCE BETWEEN RCW I AND ROW I+1.  FIRST(II) - COLUMN MUMBER OF FIRST CALCULATED GRID POINT IN FCW I.  FIRST(II) - COLUMN MUMBER OF FIRST CALCULATED GRID POINT IN FCW I.  FIRST(II) - COLUMN CONTENT IN THE RELAXATION.  FIRST - NUMBER OF COMPUTED POINTS IN GRID.  NPTS - VERTICAL RATE OF HEAT FLOW.  TEMP. ROLS. JFIRST HOSS IF NAX II.S)  TEMP. ROLS. JFIRST HOSS IF NAX II.S)  TEMP. ROLS. JFIRST HOSS IF NAX II.S)  TEMP. ROLS. JFIRST HOSS II.S IN ROLS II. LAST(20)  TEMP. ROLS. JFIRST HOSS II.S IN FRED (20)  TEMP. ROLS. JFIRST HOSS II.S IN FRED (20)  TEMP. ROLS. JFIRST HOSS II.S IN FRED (20)  TEMP. ROLS. JFIRST HOSS II.S IN THE RELAXATION.  (FIXED AT I.S)  TEMPEROLS. JFIRST HOSS II.S IN THE RELAXATION.  (FIXED AT I.S)  TEMPEROLS. JFIRST HOSS II.S IN THE RELAXATION.  (FIXED AT I.S)  TEMPOROLS. JFIRST  HEAD(20)  JEMPEROLS. JFIRST  HEAD(20)  JEMPEROLS. JFIRST  JEMPEROLS. JEMPEROLS. JEMPEROLS. JFIRST  JEMPEROLS. JEMPEROLS	SKIKK	2	ı	TIVITY OF THE	AR000130
AXTOL - ALLOWABLE AVERAGE TEMPERATURE CHANGE IN DEGREES F BETWEEN ITERATIONS.  EDGE(I) - ALLOWABLE TEMPERATURE CHANGE AT ANY GRID POINT PER ITERATIONS.  EDGE(I) - TEMPERATURE ON THE EDGE AT ROW I.  DIST(I) - VERTICAL DISTANCE TO ROW I.  Z(I) - DISTANCE EETWEEN ROW I AND ROW I+1.  FIRST(I) - COLUMN NUMBER OF FIRST CALCULATED GRID POINT IN ROW I THAT ARE NOT CLWMNS I AND I+1.  FIXED - NUMBER OF COMPUTED POINTS IN GRID.  - VERTICAL RATE OF HEAT FLOW.  - VERTICAL RATE OF HEAT FLOW.  TEMP, RDIST, ZDIST, ABSDIF, DIFSUM, OMEGA, DIFMAX  ST.NROWS, NCOLS, JF (RSI HEAD(20)  TEMP(20, 20), TEDGE(20), ZDIST(20), NFIXED(20)  100  ) = 0	XXMET	لع	•	OF THE	AR000150
AXTOL - ALLOWABLE TEMPERATURE CHANGE AT ANY GRID POINT PER ITERATION.  EDGE(I) - TEMPERATURE ON THE EDGE AT ROW I.  DIST(I) - VERTICAL DISTANCE TO ROW I.  Z(I) - DISTANCE EFTWEEN ROW I AND I+1.  R(I) - DISTANCE EFTWEEN COLUMNS I AND I+1.  FIRST(I) - COLUMN NUMBER OF FIRST CALCULATED GRID POINT IN ROW I THAT ARE NOT COMPUTED POINTS IN ROW I THAT ARE NOT COMPUTED POINTS IN GRID.  - VERTICAL RATE OF HEAT FLOW.  TEMP, RDIST, ZDIST, ABSDIF, DIFSUM, ONE GA, DIFWAX  ST, NRODES, MCOLS, JF (RST  TEMP, RDIST, ZDIST, ABSDIF, DIFSUM, ONE GA, DIFWAX  ST, NRODES, MCOLS, JF (RST  TEMP(20,20), TEDGE(20), ZDIST(20), NFIXED(20)  DECERO, OR (20), DIFF(10), JFIRST(20), NFIXED(20)	AVGTC	ų	1	E AVERAGE TEMPERATURE BY E RETHERN TEDATION	ARG00170
ANTOL - ALLOMARE TEMPERATURE CHANGE AT ANY GRID POINT PER ITERATION.  EDGE(I) - TEMPERATURE ON THE EDGE AT ROW I.  DIST(I) - DISTANCE FROM CENTER TO COLUMN I.  Z(I) - CISTANCE EFTWEEN ROW I AND ROW I+1.  Z(I) - CISTANCE EFTWEEN COLUMNS I AND I+1.  FIRST(I) - COLUMN MUMBER OF FIRST CALCULATED GRID POINT IN FOW I.  FIXED - NUMBER OF POINTS IN ROW I THAT ARE NOT COMPUTED POINTS IN GRID.  - VERTICAL RATE OF MEAT FLOW.  TEMP.RDIST.ZDIST.ABSDIF.DIFSUM.OMEGA.DIFMAX  ST.NROWS.NCOLS.JFIRST  TEMP(20.20). TEDGE(20). ZDIST(20). NFIXED(20)  DZ(20).DR(20). DIFF(10). JFIRST(20). NFIXED(20)					ARC00160
EDGE(I) - TEMPERATURE ON THE EDGE AT ROW I.  DIST(I) - VERTICAL DISTANCE TO ROW I.  Z(I) - DISTANCE FROM CENTER TO COLUMN I.  Z(I) - DISTANCE ETWEEN COLUMNS I AND I+1.  FIRST(I) - COLUMN MUMBER OF FIRST CALCULATED GRID POINT IN FCW I.  FIXED - NUMBER OF POINTS IN ROW I THAT ARE NOT CCMPUTED POINTS IN GRID.  - VERTICAL RATE OF HEAT FLOW.  - VERTICAL RATE OF HEAT FLOW.  - VERTICAL RATE OF HEAT FLOW.  TEMP.RDIST.ZDIST.ABSDIF.DIFSUM.OMEGA.DIFWAX  ST.NNOWS.NCOLS.JFIRST  HEAD(20.20). TEDGE(20). ZDIST(20). NFIXED(20)  DZ(20).DR(20). DIFF(10). JFIRST(20). NFIXED(20)	MAXTO	<u>-</u>	•	TEMPERATURE CHANGE AT I PER ITERATION.	ARD 00190 ARD 00195
DIST(I) - VERTICAL DISTANCE TO ROW I.  DIST(I) - DISTANCE EFTWEEN TO COLUMN I.  Z(I) - DISTANCE EFTWEEN COLUMNS I AND I+1.  R(I) - COLUMN NUMBER OF FIRST CALCULATED GRID POINT IN FOW I.  FIRST(I) - COLUMN NUMBER OF FIRST CALCULATED GRID POINT IN FOW I THAT ARE NOT COMPUTED POINTS IN GRID.  - VERTICAL RATE OF HEAT FLOW.  - ACCELERATION CONSTANT IN THE RELAXATION.  - FIRST(I) - ACCELERATION CONSTANT IN THE RELAXATION.  - FIRST(I) - OIFF(IO). JFIRST(20). NFIXED(20)  DE (20). OR (20). DIFF(IO). JFIRST(20). NFIXED(20)	4004			cuombatiles ou tun soms at bon .	AR000210
DIST(I) - VERTICAL DISTANCE TO ROW I.  DIST(I) - DISTANCE EETWEEN RCW I AND ROW I+1.  Z(I) - DISTANCE EETWEEN COLUMNS I AND I+1.  FIRST(I) - COLUMN MUMBER OF FIRST CALCULATED GRID POINT IN RCW I.  FIRED - NUMBER OF POINTS IN ROW I THAT ARE NOT CCMPUTED.  NPTS - NUMBER OF COMPUTED POINTS IN GRID.  - VERTICAL RATE OF HEAT FLOW.  (FIXED AT 1.5)  TEMP, RDIST, ZDIST, ABSDIF, DIFSUM, DNEGA, DIFMAX  ST.NROWS, NCOLS, JFIRST  HEAD(20)  TEMP(20, 20), TEDGE(20), JFIRST(20), NFIXED(20)  DECEND.					AR000230
Z(I) - DISTANCE FROM CENTER TO COLUMN IO Z(I) - DISTANCE EETWEEN ROW I AND IONION IONIONIS I AND IONIONIS IN ROW I THAT ARE NOT COMPUTED POINT IN FOW I THAT ARE NOT COMPUTED POINTS IN GRIDONIS IN ROW I THAT ARE NOT COMPUTED POINTS IN GRIDONIS IN CRIDONIS IN THE RELAXATION (FIXED AT 1.5)  TEMPORAL - ACCELERATION CONSTANT IN THE RELAXATION (FIXED AT 1.5)  TEMPORAL - ACCELERATIONIS IN THE RELAXATION (FIXED AT 1.5)	Z015T		•	DISTANCE TO ROW	ARG00240
R(I) - DISTANCE EETWEEN RCW I AND ROW I+1.  R(I) - DISTANCE EETWEEN COLUMNS I AND I+1.  FIRST(I) - COLUMN NUMBER OF FIRST CALCULATED GRID POINT IN FCW I.  FIXED - NUMBER OF POINTS IN ROW I THAT ARE NOT CCMPUTED.  - VERTICAL RATE OF HEAT FLCW.  - VERTICAL RATE OF HEAT FLCW.  - VERTICAL RATE OF HEAT FLCW.  (FIXED AT 1.5)  TEMP, RDIST, ZDIST, ABSDIF, DIFSUM, ONE GA, DIFMAX (FIXED AT 1.5)  TEMP(20, 20), TEDGE(20), ZDIST(20), NFIXED(20)  TEMP(20, 20), TEDGE(20), JFIRST(20), NFIXED(20)	ROIST		1	ISTANCE FROM CENTER TO COLUMN	ARC00260
FIRST(1) - OISTANCE BETWEEN COLUMNS 1 AND 1+1.  FIXED - COLUMN NUMBER OF FIRST CALCULATED GRID  FIXED - NUMBER OF POINTS IN ROW 1 THAT ARE NOT  CCMPUTED.  - VERTICAL RATE OF HEAT FLOW.  - VERTICAL RATE OF HEAT FLOW.  TEMP, RDIST, ZDIST, ABSDIF, DIFSUM, ONE GA, DIFMAX  ST.NROWS, NCCLS, JFIRST  HEAD(20)  TEMP(20, 20), TEDGE(20), JFIRST(20), NFIXED(20)  DZ(20), OR(20), DIFF(10), JFIRST(20), NFIXED(20)	0201	-	•	SET BEEN BOW I AND BOW I+1	AR000270
FIRST(1) - OISTANCE BETWEEN COLUMNS 1 AND 1+1.  FIRST(1) - COLUMN NUMBER OF FIRST CALCULATED GRID  FIXED - NUMBER OF POINTS IN ROW 1 THAT ARE NOT  CCMPUTED.  - VERTICAL RATE OF HEAT FLOW.  - VERTICAL RATE OF HEAT FLOW.  - VERTICAL RATE OF HEAT FLOW.  FIXED AT 1.5)  TEMP.RDIST.ZDIST.ABSDIF.DIFSUM.ONEGA.DIFMAX  ST.NMOWS.NCOLS.JFIRST  HEAD(20)  TEMP(20.20). TEDGE(20). ZDIST(20). NFIXED(20)  DZ(20).OR(20).  1 = 0					ARG00290
FIRST(!) - COLUMN NUMBER OF FIRST CALCULATED GRID POINT IN FCW !.  FIXED - NUMBER OF POINTS IN ROW ! THAT ARE NOT CCMPUTED.  - VERTICAL RATE OF HEAT FLOW.	08(1)	_	•	BETWEEN COLUMNS I AND	AR000300
FIXED - NUMBER OF POINTS IN ROW I THAT ARE NOT CCMPUTED.  NPTS - NUMBER OF COMPUTED POINTS IN GRID.  - VERTICAL RATE OF HEAT FLCD.  - VERTICAL RATE OF HEAT FLCD.  TEMP, RDIST, ZDIST, ABSDIF, DIFSUM, OMEGA, DIFMAX ST. NROWS, NCOLS, JF (RST HEAD(20) TEMP(20, 20), TEDGE(20), ZDIST(20), NF IXED(20) DZ(20), CR(20), DIFF(10), JF IRST(20), NF IXED(20)	JF IRS	-	1	NUMBER OF FIRST CALCULATED	ARD00320
FIXED - NUMBER OF POINTS IN ROW I THAT ARE NOT CCMPUTED.  - VERTICAL RATE OF HEAT FLOW.  - VE				OINT IN FOU	AR000321
CCMPUTED.  NPTS - NUMBER OF COMPUTED POINTS IN GRID.  - VERTICAL RATE OF HEAT FLOW.  (FIXED AT 1.5)  TEMP.RDIST.ZDIST.ABSDIF.DIFSUM.ONEGA.DIFMAX ST.NROWS.NCOLS.JFIRST HEAD(20) TEMP(20.20). TEDGE(20). ZDIST(20). RDIST(20) DZ(20).OR(20). DIFF(10). JFIRST(20). NFIXED(20)  ) = 0	NFIXE	Ö.	•	F POINTS IN ROW I THAT ARE	AR000325
NPTS - NUMBER OF COMPUTED POINTS IN GRID.  - VERTICAL RATE OF HEAT FLOW.  (FIXED AT 1.5)  TEMP, RDIST, ZDIST, ABSDIF, DIFSUM, ONE GA, DIFMAX ST.NROWS, NCOLS, JFIRST HEAD(20) TEMP(20,20), TEDGE(20), ZDIST(20), RDIST(20), LAST(20) DZ(20), OR(20), DIFF(10), JFIRST(20), NFIXED(20)				CC#PUTED.	AR000326 AR000330
- VERTICAL RATE OF HEAT FLCD.  MEGA - ACCELERATION CONSTANT IN THE RELAXATION.  (FIXED AT 1.5)  TEMP, RDIST. ZDIST. ABSDIF, DIFSUM, ONE GA, DIFMAX  ST. NROWS, NCOLS, JF (RST HEAD(20)  TEMP(20, 20), TEDGE(20), ZDIST(20), RDIST(20)  DZ(20), DR(20), DIFF(10), JF (RST(20), NF (XED(20))  ) = 0	XNPTS		1	OF COMPUTED POINTS IN	ARG00340
MEGA — ACCELERATION CONSTANT IN THE RELAXATION.  (FIXED AT 1.5)  TEMP.RDIST.ZDIST.ABSDIF.DIFSUM.ONEGA.DIFMAX ST.NROWS.NCOLS.JFIRST HEAD(20) TEMP(20.20). TEDGE(20). ZDIST(20). RDIST(20) DZ(20).OR(20). DIFF(10). JFIRST(20). NFIXED(20) 100	a		•	BATE OF	AP000350
MEGA — ACCELERATICN CCNSTANT IN THE RELAXATION.  (FIXED AT 1.5)  TEMP.RDIST.ZDIST.ABSDIF.DIFSUM.DNEGA.DIFMAX ST.NRDWS.NCOLS.JFIRST  HEAD(20)  TEMP(20.20). TEDGE(20). ZDIST(20). RDIST(20)  DZ(20).DR(20). DIFF(10). JFIRST(20). NFIXED(20)  100	1				AR000370
TEMP.RDIST.ZDIST.ABSDIF.DIFSUM.DMEGA.DIFMAX ST.NMBUS.NCGLS.JFIRST HEAD(20) TEMP(20.20). TEDGE(20). ZDIST(20). RDIST(20). LAST(20) DZ(20).GR(20). DIFF(10). JFIRST(20). NFIXED(20) 100	OMEGA		ı	IN THE	AP000360 ARC00385
ST.NROWS.NCGLS.JF(RST HEAD(20) TEMP(20,20), TEDGE(20), ZDIST(20), RDIST(20), LAST(20) DZ(20), CR(20), DIFF(10), JFIRST(20), NFIXED(20) 100		TEMP. RC	) I S T.	ZDIST.ABSDIF.DIFSUM.DNEGA.DIF WAX	AR000400
TEMP(20.20), TEDGE(20), ZDIST(20), RDIST(20), LAST(20) DZ(20), DR(20), DIFF(10), JFIRST(20), NFIXED(20) 100	CONNENS LASTON DIMENSION YES	VROES.1	AC OF:	5. JT LAST	AR000410
166		1P ( 20	23.5	EDGE(20). ZDIS1(20). RDIS1(20).	AF000430
	-	B. ( 02 )	6	DIFF(10), JFIRST(20),	AR000440 AR000460
	î Z	•			ARG00460

Table 2: Program

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ARD 00960
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 A000A
                4RD00500
                                 AR000510
                                                                                                                   CONTRACTOR THE THERMAL CONDUCTIVITY FOR THE INSCLATION 1918-9-50
                                                                                                                                                                                                                                          69 FORMAT (*0 NOTE THE UPPER LEFT HAND CORNER IS THE TOP CENTER* * ** OF THE PISTON OR VALVE.*)
                                                                                                                                                                                      FO FORMAT ("O THE FOLERANCE FOR MAXIMUM CHANGE IN TEMPERATURE IS
                                                                                                                                    THE THERMAL CONDUCTIVITY FOR THE METAL IS ".F9.5)
                READ(5,10) NROWS,NCOLS,NRUNS,XKINSL,XKMETL,AVGTOL,DIFTOL
                                                                                                                                                     19 FORMAT(*0 THE TOLERANCE FOR CHANGE IN AVG ELEMENT TEMP* ** * BETWEEN THERATIONS IS **F9*5)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          INCERPORATE EDGE CATA INTO TEMPERATURE MATRIX.
                                                                                                                                                                                                                                                                                                                                                                                                                                                                      READ( 5,90) ( TEDGE( 1 ).ZD1ST( 1) .LAST( 1) .T = 1 .NRDWS
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            THE LAST CARD READ SHOULD HAVE 1=20 AND J=20.
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     INITIALIZE THE INTERIOR OF THE TEMP MATRIX.
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                READ(5,110) (TEMP(1,J),ROIST(J),JE1,NCOLS)
                                                                                                                                                                                                                                                                                                                                                                                                                                    REAC THE CATA FROM THE PISTON EDGE.
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  READ DATA FROM PISTON SURFACE.
                                                                                                                                                                                                                                                                                                                                                                                 MAITE(6,80) (PEAD(KK), KK=1,20)
                                                                                                                                                                                                                                                                                                                                                READ(5.70) [HEAD(KK).KK=1,20)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      REAC REMAINING DATA IF ANY
                                                                                                                                                                                                                                                                                                                                                                                                      10x ,2044)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                IF (1+J .LT. 40) GD TD 130
REAC PROGRAM FARAMETERS
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                NFIXED(I) = NFIXED(I) +1
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       FORMAT (F10.3.F9.3.12)
                              FORMAT (315.6X.4F10.7)
                                                                                                                                                                                                                                                                                                                              DO 270 LOOP = 1.NRUNS
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             TEMP(1.J) = TEDGE(1)
                                                                HRITE (6,30) HKHETL
                                                ARITE(6.20) XKINSU
                                                                                 ARITE(6,40) AVGTOL
YRITE(6,50) CIFTOL
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           9EAD(5,140) 1,J.T
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                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          DO 100 I=2.NROWS
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  JFIRST(I) = J+1
                                                                                                                                                                                                                                                                                              NAME = NFOWS -1
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     110 FORMAT(2F10.3)
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NFIXED(1) = 0
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Table 2: Continued

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                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                SET UF DUMMY ROW TO SIMULATE INSULATION AT BOTTOM OF CROWN.
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 HOLD = (D20XKINSURTEMP(1,J)+D10XK0ETL0TEMP(3,J))/(D20XKINSU
                                                                                                                                                                                                                                                                                                                                                                                                                                                                 SWEEP FOW 2 (WHERE THE INSCLATICH MEETS THE METAL).
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   CALCULATE CENTERLINE ELEMENT IF NEECEC.
                                                                                                                                                                                                                 COMPUTE THE DISTANCES BETWEEN ROWS.
                                                                                                                                                                                                                                                                                                                           COMPUTE DISTANCE BETWEEN COLUMNS.
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 TEMP(NEGES+1,J) = TEMP(NRCWS-1,J)
                                                                                                                                                                                                                                                                                                                                                       DO 170 J=1.AC#1
DR(J) = RDIST(J+1) - RDIST(J)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              IF (JFIRST(1). (E.2) GO TO 200
                                                                                                                                                                                                                                                         OZ(1) = ZDIST(1+1) -ZDIST(1)
CONTINLE
                                                                                                                                                                                                                                                                                                                                                                                                            BEGIN FELAXATION SWEEPS.
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     SWEEP FORE 3 TO NEOUS
                                                                                                                                              INITIAL IZE COUNTERS.
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        COMAB = DA+DB+(CA+DB)
                                                                                                                                                                                                                                                                                 DZ (NRO 15) = CZ (MRM1)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               CALL RELAX(2.1.HOLD)
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                                                                                         ANDIS A ANDIS + 1.0
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                      20 150 I=2,NR3#S
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          DO 180 J=1 .NCM1
                                                                                                                                                                                                                                            DO 160 I=1.NEM1
                                                                           TEMP(1,3) =0.0
                                                                                                                                                                                                                                                                                                THICK = DZ(1)
                                                 JT= JF IRST(1)
                                                             30 15G J=J1.K
                                                                                                                                                                          DIFMAX = C.0
                                    <= LAST(1) -1
                                                                                                                                                                                      DIFSUR # 0.0
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         CAPTS = 3.0
                                                                                                                   TALL OLTPUT
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                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     01 = 52(1)
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Table 2: Continued

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ARO 81860
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                                                                                                                                                                                                                                ARG0 18 20
                          HOLD = 2.4CChabtemp(1,2)+DRSG4(DE+TEMP(1-1,1) +DA+TEMP(1+1,1))
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              G= 0 + (RDIST(KO+1)++2-RDIST(KO)++2)+(TEMP(KR+KO)+TEMP(KR+KO+1)
                                                                                                                                                                                                                                                                                                                                                                                                                            HOLD = HOLD + CGNAB#D2#(TWORAD-02) + TEMP(I.J-1)

HOLD = HOLO + TEORAD + CONLR +(DB#TEMP(I-I.J.)+DA#TEMP(I+I.J.))
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 WRITE(6,240) Q
FORMAT(//*ITFE TOTAL HEAT FLOW RATE IS *, FI6.5, BTU/HR*)
                                                                                                                                                                                            CHECK IF CENTERLINE ELEMENT HAS BEEN CALCULATED.
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                250 FORMAT (// OTHE NUMBER OF ITERATIONS NAS .. 14)
                                                                                                                                                                                                                                                                                                                                                                                                              HOLD = CONAB + D1 + (C1+TWDRAD)+TEMP(1,3+1)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                CHECK FOR CONVERGENCE.
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                COMPUTE THE TOTAL RATE OF HEAT FLOW (Q)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                TEMF(KR+1.KQ) -TEMF(KR+1.KQ+1))/2.0
DRSG # DR(1)+CR(1)
JENOM = 2.0+CONAB + DRSG # (DA+DB)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            IF (AVCDIF.GT. AVCTOL) GO TO 260
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               O= 3.14159*XKMETL+0/12.0 /DZ(KR)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                IF ( DIFER GT DIFTOL) GO TO 260
                                                                                                                                                                                                                                                                                                                                                                             # TEGRAD 4 CONAB 4 (C1+D2)
                                                                                                                                                                                                                                                                                                                                                                                             C3 = TWORAD + CCNLR + (CA+DB)
                                                                                                             FINISH SWEEP ING THE ACK.
                                                                                                                                                                                                                                                                                                                         TWORAD = 2. + RAD
CONLR = 02 + D1+ (02 + D1)
                                                                                                                                                                                                                                                                                                                                                               C1 = CONAB#(D1#D1 -D2#D2)
                                                                                                                                                                                                                                            1F (JENC.LT.JT) GO TJ 220
                                                                                                                                                                                                                                                                                                                                                                                                                                                           HOLD = HOLD /(C1+C2+C3)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              AVGDIF . DIFSUM / XNPTS
                                                                                                                                                                                                                                                                                                                                                                                                                                                                               CALL RELAX(I,J,HOLD)
                                                          CALL FELAX(I. I. FOLD)
                                                                                                                                                                                                                              IF (JT.E0.1) JT = 2
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                SWEEP COMPLETE.
                                                                                                                                             JEND = LAST(I) -1
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                DO 230 KG=1.NCM1
                                                                                                                                                                                                                                                              00 210 J=JT.JEND
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 WRI TE(6,250) M
                                                                                                                                                                                                                                                                                                             RAD = FD1ST(J)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               DIFER = DIFMAX
                                                                                                                                                             JT = JFIRST(1)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                DIFSUM = 0.0
                                                                                                                                                                                                                                                                               01 = DR(J-1)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                DIFMAX = 0.
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               CALL DUTPUT
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 CALL DUTPUT
                                                                                                                                                                                                                                                                                               D2 = DR( J)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 GO TO 270
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Table 2: Continued

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Table 2: Continued

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Table 3 Sample Data Cards

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Table No. 4: Program Output

to surface temperatures, certain interior temperatures are needed to develop the mathematical model. For these reasons, a program was undertaken to establish operational temperatures for a ceramic coated piston and exhaust valve. Needed information included temperature data at known points for various power levels for uncoated parts and for parts with 0.040 inch, 0.070 inch and 0.100 inch coating of plasma sprayed yttrium stabilized zirconium oxide.

## TEST FACILITIES

The engine selected for acquisition of temperature data was the same as that used for the previous performance data of ceramic coated parts. This was a cooperative fuel research (CFR) engine incorporating the low speed crankcase and the split cylinder head. The engine and the associated laboratory are shown in figure 12. An engine schematic is illustrated in figure 13.

Intake air was drawn through an ice tower to control humidity. It then passed through a flow control system consisting of a laminar flow element, a surge chamber and a throttle valve. By this method a constant humidity, pressure and temperature of air was available to the engine for all tests.

Fuel for all tests was commercial liquified petroleum gas (LPG).

Lubricating oil temperature was controllable by an electric heater

located in the oil sump. Engine cooling was by the standard CFR boiling water jacket.

Engine power output was measured by an indicated mean effective pressure (IMEP) method. This technique incorporates a strain gauge pressure transducer located in the combustion chamber, an engine rotational position transducer on the crankshaft and a cycle indicator located on the camshaft. These three transducers provide the necessary data input to a PET 2001-8 computer for the solution of the following equation:

$$IMEP = \int pdv \qquad (20)$$

The average of several of the above solutions provides an average

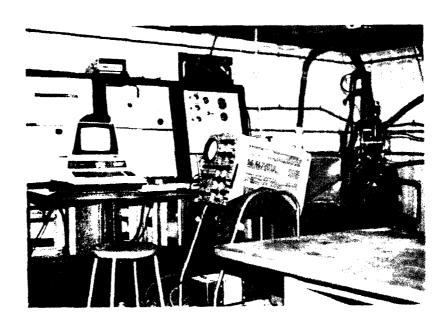


Figure 12: Engine Laboratory

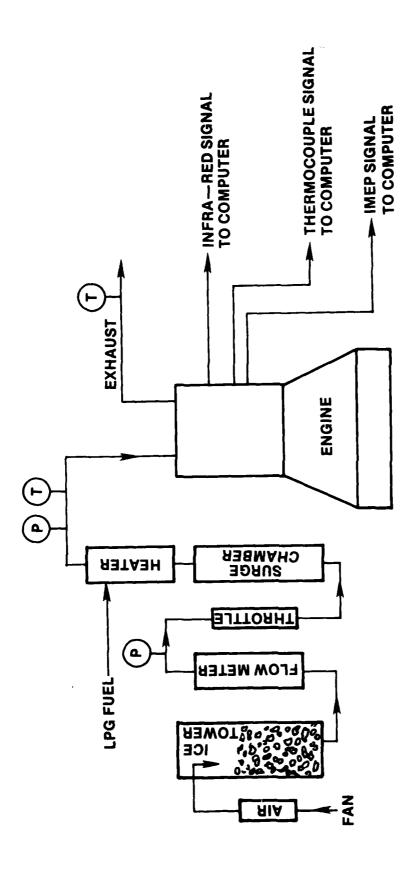


Figure 13: Engine Schematic

value of the IMEP for any operational condition. This value is recorded as engine power level.

Those familiar with temperature measurement recognize the problems in establishing accurate data at point sources in ceramic substances. Such sources on the interior of metallic parts also offer a significant challenge. Finally, when one locates these points on a reciprocating piston (valve) of an operational engine, the full complexity of the situation becomes apparent.

The above problem can be subdivided into two parts: 1) what method should be used to measure each point temperature, and 2) how should the signal be transmitted from moving parts to the exterior of the engine?

Historically, thermocouples (including thin film deposited types), deposited thin film resistors, thermisters and Templugs have been successfully used for general temperature measurement.

Plasma sprayed surfaces are relatively porous which would greatly reduce the probability of successful application of thin film deposited type devices. Ceramic surfaces that are attached to a metal structure make the attachment and routing of leadwires nearly impossible.

In this project, the ceramic surface must be reduced from 0.100 inch thickness to zero in three stages by a surface grinding technique. Such a process would necessarily destroy any surface device and require the reinstallation and recalibration of a new one.

Templugs are a threaded metal insert that measure temperature by hardness change. These devices measure only the peak temperature and would not be compatible with a plasma sprayed surface.

Recognizing the problems with temperature measurement on a ceramic surface in the combustion chamber of a reciprocating I-C engine, it was decided that optical techniques offered the best hope of success.

It is known that all surfaces emit an infrared radiation as a direct function of surface temperature. Therefore, if this signal could be viewed and transmitted outside the engine, a method would have been found to instantaneously measure surface temperature without touching or affecting the surface.

The infrared signal transmission problem was solved by a system of water cooled probes that incorporated a glass fiber optics bundle. One bundle was designed so it could view both the top and surface of the piston and the lower surface of the exhaust valve. Both of these surfaces were within the chamber. A second bundle was used to view the exhaust valve tulip (manifold) surface. Details of these probes and associated hardware follows.

Figure 14 shows details of an actual fiber optics bundle and the water cooled probe into which it is assembled. This probe is shown in position on the engine in figure 15. Note that the probe fits into a deck spacer between the engine cylinder and cylinder head. This technique allows the probe to be moved in and out to view various radial positions and to be rotated 180° to alternately inspect the piston and the valve surface.

Figure 16 displays details of a second water cooled probe designed to view the exhaust valve tulip. Installation of this probe into the CFR cylinder head is seen in figure 17.

The optical signal from both of these probes is transmitted by flexible fiber optics to a detector that converts the I-R signal to an electric voltage. The electric signal is read as a temperature by an analyzer.

During the tests the PET 2001-8 computer seved as the I-R temperature readout device, reading each probe temperature at a selected engine position. For the piston, the reading position was the top dead center (TDC) position on the exhaust-intake overlap event. The combustion chamber valve surface was read at this same cyclic position. The valve tulip was monitored with the valve closed at the BDC position at the end of the intake stroke.

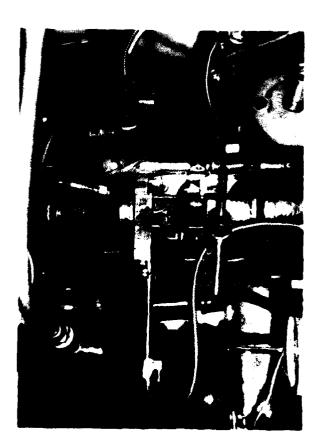
## SEMIADIABATIC PISTON

As stated previously, piston temperatures were required both on the combustion chamber and crankcase surfaces, as well as on selected points on the interior of the metallic structure. Instrumentation plans called for the piston combustion chamber surface to be measured



Figure 14: Fiber Optics
Combustion Chamber

Figure 15: Combustion Chamber Probe Installation



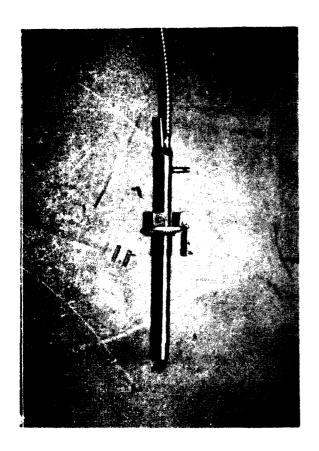
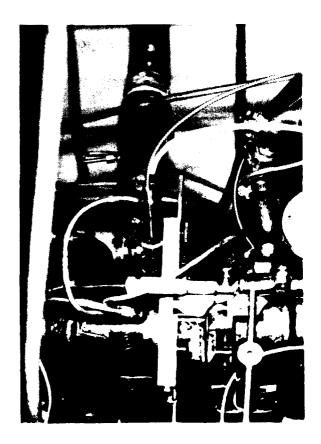


Figure 16: Fiber Optics Exhaust Port

Figure 17: Exhaust Port
Probe Installation



by an infrared probe while all other temperatures used thermocouples.

The basic piston design adopted is seen in cross section in figure 18 and in assembly in figure 19. This is a three component piston consisting of a steel crown, a phenolic spacer and an aluminum skirt in assembly. The crown is fastened to the skirt by a series of screws.

The piston crown is a symmetrical design (to insure two direction heat flow) with access holes drilled for interior thermocouple insertion. These thermocouples were held in place by a ceramic cement. Other thermocouples are attached to the lower surface by peening. Figure 20 identifies the position of the eleven thermocouples used. Figure 21 shows the piston crown with thermocouples installed. Also shown, in position, is the phenolic insulator. Note that a series of holes have been designed into each side of the insulator. These holes provide a screw type connection between the fine wire (0.015 inch) iron constantan thermocouples and the stranded 30 gauge leadwire. Thirteen wires are routed through the piston skirt shown in figure 22 and 23; two of these wires served as redundant commons while the other eleven were signal wires for each of the eleven thermocouples.

## THERMOCOUPLE WIRE ROUTING

Leadwire termination on the piston was by high temperature epoxy, as was the attachment to the connecting rod. Note in figure 24 that stress relief loops have been placed at the junction between the piston and connecting rod.

At the big end of the connecting rod another stress relief loop joined the span between the connecting rod and the swivel of a multibar support mechanism. This mechanism was designed to penetrate the crankcase at a sliding-rotating bearing and provide support for the thermocouple leadwires. An exterior view of this device is seen in figure 25. The base of the multibar mechanism is a pin joint attached to the engine baseplate. The thermocouple wires continue from this location through a selector switch to computer and digital readout.

The exhaust valve configuration without ceramic coating is shown

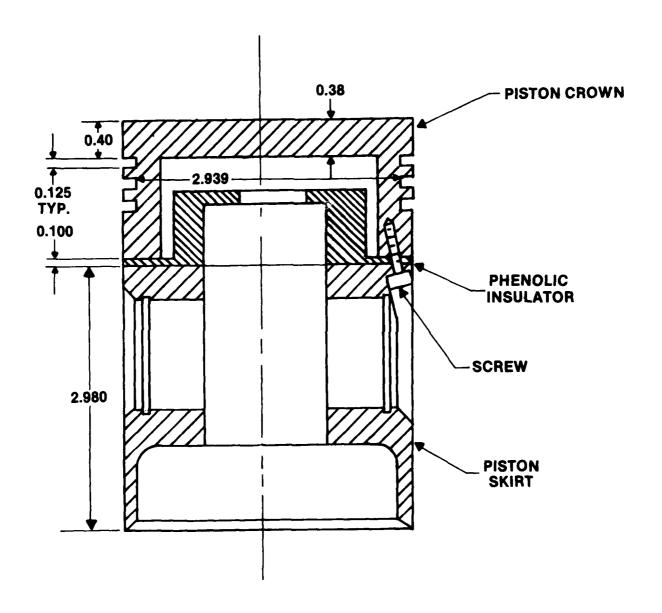


Figure 18: Piston Cross Section



Figure 19: Piston Assembly

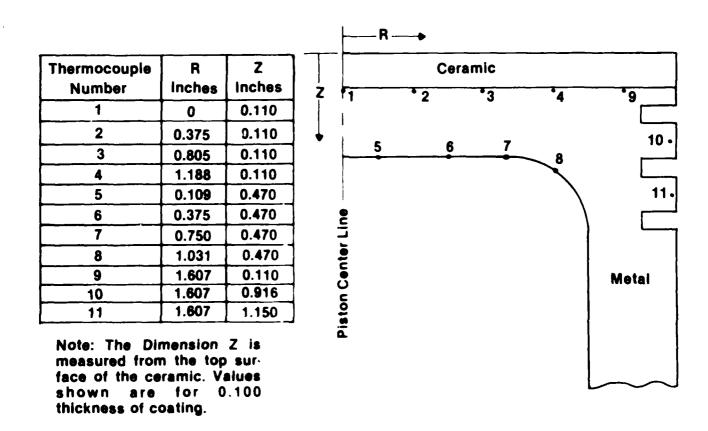


Figure Do Them as .. Let Sition



Figure 21: Thermocouple Installation

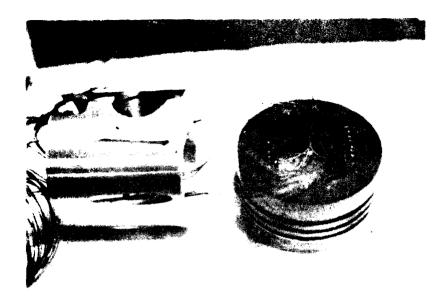


Figure 22: Piston Leadwire Installation

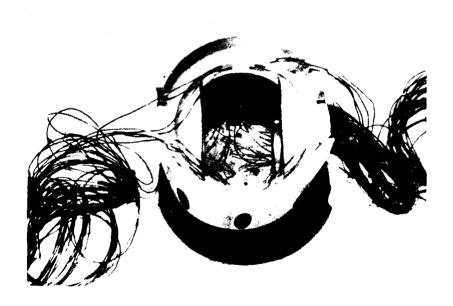
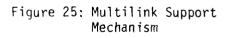
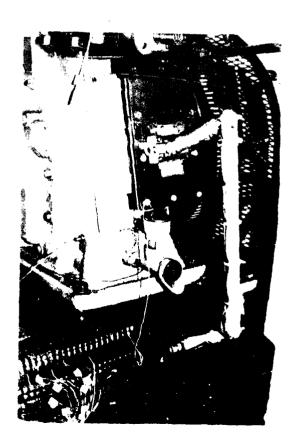


Figure 23: Piston Leadwire Routing



Figure 24: Piston-Connecting Rod Assembly





in figure 26. As with the piston a 0.100 inch coating of yttrium stabilized zirconium oxide was applied by plasma spray. Coating thickness was reduced to 0.070, 0.040 and 0.000 inches for repeated tests. Controlled valve seat contact was established by hand grinding, lapping and fitting. Special gauges were fabricated to insure repeatability of valve seat contact. The valve grid network utilized in this test is defined by radial locations as viewed by the fiber optics probe and as portrayed in figure 27.

# ENGINE ASSEMBLY

Figure 28 portrays the engine as assembled for final test. Noteworthy items are:

- (A) Engine rotational position transducers
- (B) Cycle position transducer
- (C) Multibar support mechanism
- (D) Deck spacer with fiber optics.

Engine test specifications follow in table 5:

#### Table 5

Bore	3.25 inch
Stroke	4.50 inch
Compression ratio	6.5 to 1
Cooling water temperature	210° F
Lubricating oil temperature	120° F
Ignition timing	10° BTDC
RPM	630
Fuel	Commercial liquified
	Petroleum gas

## TEST PROCEDURE AND DATA

The data required for ceramic coating evaluation was as follows:

- 1) Metal ceramic interface temperature or thermocouple output for numbers 1, 2, 3, 4, & 9.
- 2) Ring belt temperature or thermocouple output for number 10 & 11.

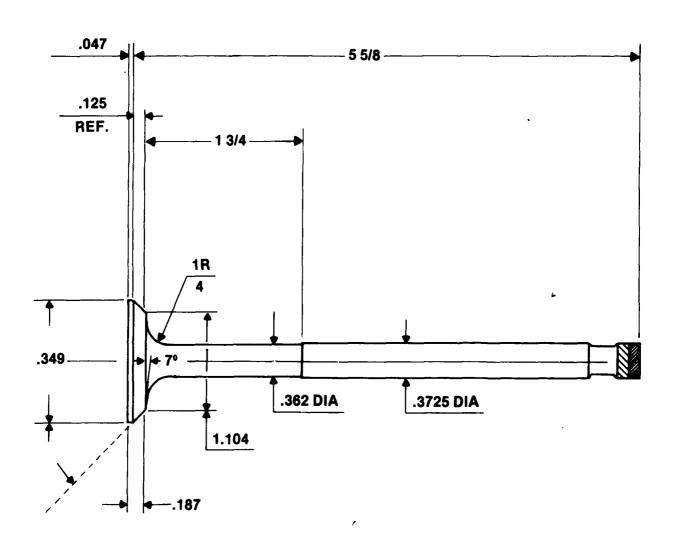
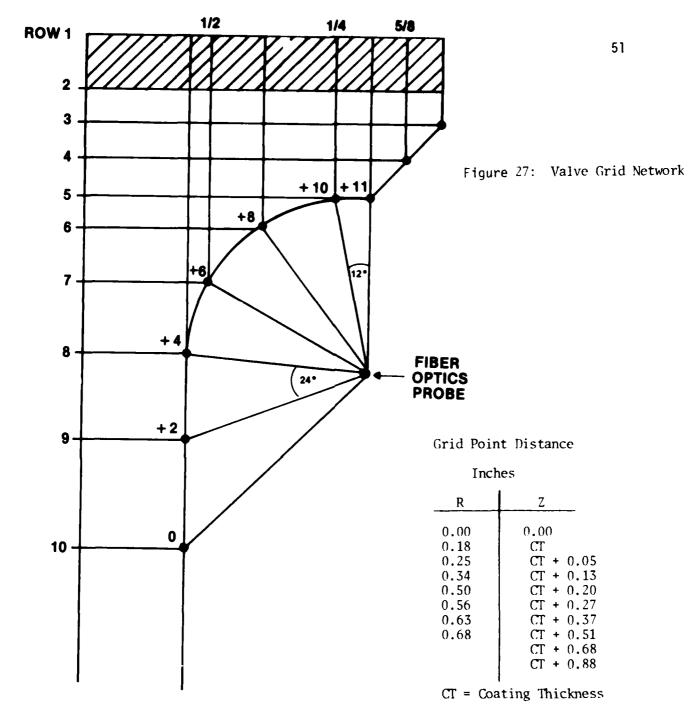


Figure 26: Valve Configuration



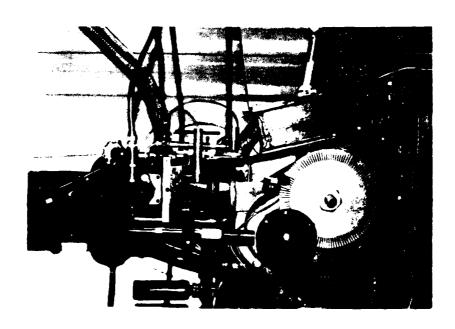


Figure 28: Engine Assembly

- 3) Crankcase surface temperature or thermocouple output for numbers 5, 6, 7, & 8.
- 4) Piston and valve combustion chamber surface or infrared output at various radial positions.
- 5) Valve tulip surface temperature at various positions.

The above data values were determined for ceramic coating thickness of 0.100, 0.070, 0.040, 0.000 inches at 5 power levels corresponding to 100%, 75%, 50%, 25% and motoring. This data is displayed in the top profiles of tables 6 & 7, respectively. Interpretation of tabulation has previously been outlined. Heat transfer and the calculated temperature and distribution is shown below the top profile. Maximum power for this version of the CFR engine corresponded to an indicated mean effective pressure of 40.5 psi. In each test, a fuel flow was established that produced this rated power. Fuel flow was incrementally reduced to produce the indicated steps of reduced power. Engine temperatures were allowed to stabilize before data was taken.

# DATA ANALYSIS

The results of the preceding calculations are displayed in tables 8 and 9. Table 8 displays heat transfer information based on boundary conditions using infrared data as well as thermocouples. Table 9 is comparative data for the piston only, based on thermocouple data.

In both cases, the data shows the expected reduction in heat flow with increased coating thickness. The correlation between the sets of data, however, is not good. The great difference in heat flow for infrared and noninfrared calculations leads one to believe that the accuracy of the surface temperature measurement is poor.

#### **ENDURANCE TEST**

As previously stated, a part of this project was to establish the endurance behavior for zirconium oxide coated engine parts. Actually, the test described, herein, was the continuation of a 1000 hour en-

CEGAMIC = 100/1000, POWER= 100 PER CENT

-35.21391BTU/HR THE TOTAL PEAT FLOW RATE IS

						Table 6	Valve Temperature Profiles			
0. 68	513.00	532.07	540.00				Valve			
0.63	513.00	540-68 538.11	536.26	532.00						
9.56	544.00		542.56	539.53						
0.57	575.00	544.16	543.58	514.70	548.00					
0.34	592.00	551.48 544.16	£54.77 553.59 551.23 543.98	552.15	554,42 548,33	558.00				
0.25	604.00	€ 53.89	553.59	554.22	556.14 555.81	558.24	563.09			
9.18	603.00	66 . 6 3 3	554.79	555.10	556.14	557.47	556.58	549.00	54%.00	527.00
00.0	59 A . 00	555.71	555.48	555.60	\$56.04	556.43	555.90	549.59	543.85	531.86
DISTANCE	300000	0.100	0 1 2 9 9	0,2300	2,3000	004295	0.4790	2. 61 00	0082.0	0.9900

CERAMIC = 100/1010, FCWER= 75 PER CENT

DISTANCE	00.0	61.6	\$2.0	0.34	9.50	9.56	0.63	0.65	
0.000	522,00	923,00	481.30	517.00	572.30	579. A	585.00	585.00	
0.1000	00.0	C. 00	0.00	0.00	0000	00.0	000	496.00	
0.1509	00.0	00.0	· · · · ·	00*0	0.00	00 00	00.00	506.00	
0.2300	00 00	00.00	0.00	00.0	00.0	00.0	496.00		
0.3000	0.00	00.0	0.00	00.0	514.00				
6.3709	00.0	0.03	00.0	522.00					
0-4706	0.0	00.00	505.00						
5.6100	0.00	£34,69							
5,7803	2.00	505-00							
0.9860	00.00	476.00							
THE TOTAL PEAT PLOW RATE IS	NT FLOW RA	TE IS	-26	-26.40177841740	9				

						Table & (continued)	Valve Temperature Drofiles		
ن• دو	565.00	496.00	506,09				2		
0.63	585.03	504,29	573.80	496.00					
99.0	579.00	506+35	517.49 515.52 514.19 578.97 505.91	539.70 504.07 496.00					
7.57	572.33	509.35	578.97		£14.70				
0.34	517.00	515.42 515.30 514.21 509.35	514,19	515.24	517.72	522.00			
0.25	923.00 491.00	515.30	515.52	515.45	514.37 515.42 517.72	512,36 514,35 522,00	505.00		
61.9	923.00	515.52	517.49	515,65	514.37	512, 36	506. 97	504.00	505.09
0000	\$2 2, 00	515.52	515.91	58 4.86	51 3 . 4 S	511.49	597.78	30 4. 46	501.93
DISTANCE	0.0000	0001.0	r.150n	0. 2300	0.3000	0.3700	30.4.0	0.6100	0.7800

501-93 505-09 464.69 476.00

0.9800

CERANIC # 1992/10/3, FGWER= 50 PER CENT

0.68	478.03	512.00	522.00								
0.63	476.00	00.0	000	512.00							
0.56	477.00	0.90	0.00	0.00							
0.50	476.00	0.00	0.00	00.00	532.00						
0.34	477.00	0.09	0.00	0000	0.00	542-00					
J• 25	477.00	00.00	٥٠٠	00 • 0	00.0	0.00	543.00				
9-19	477.03	00°0	00.0	0.00	00 %	0000	00.00	£26.00	£32.03	566.30	
00 • 0	477.00	00.00	00.0	0.00	00 00	0.00	0.00	00.0	3.09	00.0	
DISTANCE	000000	3° 136 c	0.1500	0.2300	C- 3000	0.3700	C. 4700	0. 61 00	رد87 م	C. 5800	

-78-49364PTU/FB
IS
RATE
FLCW
FEAT
TOTAL
Ŧ

DISTANCE	00 • 0	0.18	0.25	0.34	0.50	0.56	0.63	69	
300- 3	67.7.09	477.33	477.03	477.00	476.03	476.03 477.00	476.00	478,00	
0001 %	534.54	534.19	534.19 533.45	531.63	524.67 521.23	521.23	519.14	512.00	
0.1507	534.91	13.4 <b>.</b> 65	523.80	531.56		£24.9£ £21.50 519.39	515,39		
0,2370	535,73	535,73	535.73 535.31	533.90 526.65	526.65	520.26	512.00		
000200	536.46	£37.13	£37.13 537.46	537.26	532.00				
r.3700	536.70	536.37	540.01	542.30				H	7
C. 4700	535, 61	<b>536.25</b>	543.00					ומו	ਰ ਹ
0.6100	528.47	£26.00						, ,	υ
C. 7800	527.83	£32.00							
0.9800	508.02	200-00							

able 6 (continued) e Temperature Profiles

CESAMIC = 100/1000, POWER = 25 DER CENT

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.0	00.00	7518	0.25	6.34	3.50	0.56	0.63	0.68
6.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	0.00			0.03	0.00	0000	000	
6.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	00.0		00.0	00.00	0000	00.0	0000	606.00
6.00 0.00 0.00 0.00 0.00 598.00 654.00 £73.00	0.0		00.0	0.00	0.00	00 00	556.00	
0.00 0.00 0.00 590.00 554.70 £73.00	0.00		00.0	00.0	6 02 • 0 0			
654.00 #73.00 \$76.30	0.00		0.00	598.00				
	00.0		290.00					
	0. 20							
	0.00							
	•							

-110.51210BTU/HR
15
RATE
FL CW
FEAT
TOTAL
THE

STANCE	0· · c	91.6	0.25	9.34	1.51	95.0	69.63	3.68
0000 •0	476.00		476.00	476.00	475.00	475.00	476.00 476.00 476.00 475.00 475.00 475.00	475.00
0-1000	592.68	553,59	594.42 555.77	595.77	598631	598-71 595-15	600.67	595600
0.1500	593.42		595.14	596.50	599.06	16 '669	594.31 595.14 596.50 599.06 399.91 601.43 606.00	00° 909
0.230n	594.00		595-81	597.40	\$1.009	594.91 595.81 597.40 633.15 632.16	556.00	
3. 390°	59 3, 55	593.55 554.78 595.77 597.91 672.10	595.77	597.91	672.10			
0075.0	593,39	£93.97	554.77	35e, nņ				Table 6 (continued)
0,4700	591.99	591.83	200 • 00					Valve Temperature Profi
0.6190	55.0+35	554.00						
0.7800	576.49	573.00						
0.9800	576-14	57 €. 00						

CERAMIC = 100/1000, POWER OF PER CENT

DISTANCE	00.00	2.18	0.25	0.34	0.53	0.56	0.63	0° 68
00 00 00	497.03		566.00 589.00	269.00	540.00	527.00	515.00	515.00
0.1000	00°0	0.00	00.0	0.0	0.00	00.00	0.00	674.00
0.1500	0.00	0°°	00.0	00.0	0.00	0000	00.0	684.00
0.2300	00.0	00.00	00.0	0.0	0.00	0.00	674.00	
0006.0	00.0	0.00	0000	00.0	685.00			
0.3709	0.00	00.00	00.0	686.00				
0.4700	0.00	0.00	694.00					
19 <b>- 0</b>	0.00	665.00						
0.7600	00.00	675.00						
0.980 c	00.0	6.5.00						

-116.41070BTU/HR

THE TOTAL PEAT FLOW RATE IS

I STA NCE	00°0	9.18	0.25	9.34	0.53	7.56	0.63	0.69	
40 úc *p	497.00	566.00	589.00	569.00	540.00	527,00	515.00	515.00	
00-1-0	(91,67	692.42	682,34	681.47	679.49	578,62	676.87	674.03	
0.1500	682. B2	683.14	683,14 682,91	682.16	682.16 697,33	679 54	675.86 EE4.JO	€E4•Jņ	
0.7300	684.44	664.56	684 , 27	693.52	6E1.90	679.55	674.03		
0,3303	685.89	660.08	666.38 685.86		684.53 685.00				
6022100	686,99		667.84 688.01	696.00				Table	Table 6 (continued)
0.074.0	697 .01	650.37	654.00					Valve Ten	Valve Temperature Profiles
0.6100	69 3, 61	685.00							
C. 7800	674.04	675.00							
0.96.0	658,35	658.35 652.00							

CET:41C = 70/1000, FOWER = 100 PER CENT

DISTANCE	00.0	e1.0	0.25	J. 34	7.59	0.56	0.63	0.68
0000 -0	532.00	550.03	556.00	546.00	546.00 532.00	532,00		533.00 533.09
0,070.0	00.00	C0 °0	00 • 0	0.00	0.00	0.00	0.00	537.00
ن، 1200	00.0	0000	0.00	0.00	00.0	00.0	0.00	547.03
ენ ან ან	00 • 0	00.00	0.00	0.00	0.00	0.00	537.00	
0.2700	0.00	00.0	00.0	00.0	548.00			
0-3400	00.0	0.00	0 • 0	550.00				
0.44.0	00 • 0	00 -0	548.00					
0.55.00	00.0	54%.30						
C. 7500	00 00	835,30						
0.9500	00.0	#35.90						

THE TOTAL PEAT FLOW RATE IS -60.891108TU/HR

						Table 6 (continued)	Valve Temperature Profiles			
0. 68	533.00	537.00	547.03			•	Val			
0.63	533,00	543,55	547,65 547,84 547,74 547,25 545,05 543,93 542,64 547,03	537,00						
0. 5¢	532.10	543.93	543.93	545.65 543.03						
). E	532.0	544.94	545.05		519.00					
0.34	546.93	547.83 547.80 547.23 544.94 547.93 543.55	547.25	547.75	546.72	550.00				
0.25	556.00	547.80	547.74		546.11 548.36	548.19 548.55 550.00	548.00			
13،19	550,00	£47.83	547.84	547.96 547.97	546.11	546.19	£47.39	545.00	£35.00	
ن ن ن	532.00	547.50	547.65	547.70	507.78	547.58	546.76	544.33	£39,20	
PISTANCE	6006-0	0.0700	n. 1230	Co 5 3 0 3	(0-20-	C. 3409	0.4400	0.5410	6.7590	

534.08 532.00

0.9500

CEFAMIC = 73/1000, FOWERS 75 PER CENT

DISTANCE	00 • 0	0.19	0.25	0.34	0.50	95.0	0.63	0.68
000000	293.00		571.00 568.07	567.00	565+00	564.00	564.07	564.00
Co 070 a	00 00	00 00	00.0	0.00	0000	0000	0000	716.00
0.1200	00.0	0.00	00.0	00.0	60.0	0.00	0.00	726.09
0.2000	00.0	00.00	0.00	0.00	00.0	0000	716.00	
0.2700	00 00	0.00	00.0	00.00	726.00			
0.3400	00.0	0.00	00.0	727.09				
6,4400	00.0	0.00	726.00					
0.5800	00.0	716.00						
0.7500	0.0	650.00						
C0 5 2 0 0	0.00	6E5.00					•	

-153.06910BTU/FR

THE TOTAL HEAT FLOW RATE IS

						ntinued)	re Profiles		
						Table 6 (continued)	Valve Temperature Profiles		
0.68	564.33	716.00	726.0n				>		
0.63	564.03	715.98	10 715.61 719.95 720.34 720.35 72.29 721.33 726.00	716.00					
98*0	564, 90	88 716.32 718.63 719.02 719.02 718.94 715.98	*2. 2 H	723,92					
0.50	56500	719.92	720.35	722.5c	726.00				
0.34	567.00	719.92	720.34	720.79 721.46 721.97 722.5A 7?2.5¢	722.17 723.62 724.77	727.CO			
0.25	558.00	718.63	719.95	721.97	723.62	724.99	726.03		
0.18	571.90	716.32	715.61	721.46	722.17	721.88 723.57 724.99 727.CO	723.16	716.00	00°059 29
00.0	590°00	717.88	719.10	720.70	721.64	721.88	723.47	712.90	693.62
DISTANCE	0.000.0	نه 10 ن ت	0021-0	0.2700	C. 2700	0.3400	Co 4403	0 2800	٥٠٤٤٠٥

687.48 685.00

C. 9500

THE STATE & 70/10/10 STATES STATES

J. ¢3	534.00	650.00	660.00							
Caes Jacs	344.00	0.00	0000	550.00						
4 5	531.00	2:50	00.0	00.0						
·• 50	22 A. 00	0.00	0.00	0.00	00.9999					
1 2 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5	528.00	0.00	00.0	3.00	0.00	673.00				
3.45	54.2,00 (53% \$ 53,00	(O.	0.13	C0.	3.63	00 • 0	667.09			
•	(2) (3) (4)		e E	?	· · ·	C. 30	01.10	665,39	653,00	663.13
00°0	54.2.00	00.0	0.00	00.0	3.03	00.0	00.0	00.0	00.0	00°C
. 5.44.516	000000	00-11-00	1,1200	0.22.00	9-2763	00+2+0	G.4400	20,5900	6-7500	2,5503

-157.6414087UZHP

THE TOTAL PEST FLOW PATE IS

0.es	534.17	€50•03	660.00			Table 6 (continued)	Valve Temperature Profiles		
0,63		652,79		0 <b>0-0</b> 50					
3.56	528.00 531.00 344.00	661+34 661+37 560+85 657,17 (58,22 652+79	638.23 656.30 655.46	64453 664478 c64477 660436 (7655 350400					
3.53	523.00	657,17		660.36	656.03				
0.34	528.00	960.85	562.01	564.77	66fe.7 66fe93 668e33 656e03	073.00			
2.25	£32.00 528.00	661.37	662451 552453	664.78	666.93	668.63	667.03		
0.19	532.00	661.15	15"633	6.4.53	666.7	te5.90 667.05 t68.60	666.93 667.03	665,23	662.00
ئ د د د	542.00	661.43	£62.4A	564,11	665.24	05.500	655,60	663,29	654.87
DISTONCE	J. 0700	3-0700	1.1200	60020	30, 25	00 1400	6	r., 5300	C. 7500

653.54 553.00

0.055.0

5767.6	0		ζ,	<b>9</b>	(6.	0	30 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	6, 69	
6650.3	569.00	569.00 571. 1 572.03 575.30 579.03 573.00	572.03	575.30	579.03	573,00	567.00	567.00	
0040.0	00.0	€. • o	00.0	0.00	0.0	0C°Ü	0.00	685.00	
0021.0	00.0	Cr &	00° (·	0.00	3.30	00.00	0.00	655.00	
0-2000	00 °C	Ç.	00 • 0	00.0	0.00	00°0	695.00		
0.2799	٥٠٠٥	ĉ ŝ	60.0	<b>00•</b> 0	751.00				
0,3400	00 °C	0.00	0.00	0.07 738.09					
0~4400	00.0	0 . 0	200.602						
0.5800	00 °C	710.00							
00 1500	00.00	70.00 30							
0056*3	00.0	683.00							
4E TOT AL	45 TOTAL PEAT PLOW PATE IS	TE 15	-132	-132.874209TUZHR	Z + / )				

ISTANCE	0 - 0 0	2,13	3.25	0.34	3.53	96 ℃	5.63	0. 68	
2,0003	86.9 <b>•</b> 00	571.93	571.00 572.00		579.03	573,00	575.00 579.00 573.00 567.00	567.00	
00200	698.75	15.359	C1.867 F2.323	96.259	652.34	80.503	547.16 (52.34 4 CC. 9A 695.20 CB5400	C85,00	
0.1200	699.89		62.000 50.23		5 +3 4 9 3	591.99	698*12 543*93 591.00 691*26	655.00	
0. 2000	701.89		701.50	700.67	701.78 701.50 700.67 626.19 091.76 685.00	32.1167	685.00		
7,2700	70 3.69	703.99	713.58		733-54 761-63				
0.3430	705.38	706.97	705.97 706.55	738-00					Table 6 (continued)
0.4400	707.18	92.30€	7.19.00						Valve Temperature Profiles
30e3*3	707-45	710.30							
5054.0	695.4R	700-00							
0.9500	687.75	683.00							

Table 6 (continued) Valve Temperture Profiles

CERAMIC = 70/1631 FOWER = 00 PER CENT

ISTANCE	, o • o	61.0 0.00	o. 25	0.34	1.59	9,56	0.63	0.68	
3-3003	527.00	520.00 516.33	517.39	516.09	516.00 515.00		515.00 515.00	515.00	
0.0700	00.00	00 •0	00 •0	0.00	0.00	0.00	0 00 0	678.00	
0.1200	0.0	0.03	00 • 0	00.0	0.00	00.00	00.0	668.00	
0. 2709	00 00	00.00	00 • 0	00.00	0.00	00.00	678.00		
0.2700	00.0	00.5	00.0	00.0	667.00				
2+3400	0.00	3.10	00•0	685.00					
0-4400	00.00	C. 00	675.00						
0.5800	00.0	0.00 665.03							
0022.00	9° 00	667.39							
C. 9500	00.0	0.00 672.00							

-159.823008TU/FR
51
RATE
FLC
FEAT
TC T AL
7 H.R

DISTANCE	( ° °	3,18	9.25	<b>₽</b> £ • j	J. 50	3, 40	0.63	0.68	
0.000	529, ng	£13.00	513.00 517.00	516.00	515.03	515.73	515.00	515.70	
0020-0	673.68		£74.54 676.01	A77.5E	579.59	580.10	681.61	679.00	
0-1201	675.03	676.33	677.40	677.40 673.56 691.71	691.01	681, 53	682 <b>.</b> 06	698.03	
000200	676.37	676.37 677.34 679.15	679.15	691-15 691-10	04.169	632.44	678.00		
0.2790	676.59	676.25	676.25 680.01	683.10	687.00				
Co 340?	675.81	675.81 £77.59 679.73	679.73	685.00					
0.4400	672.90	673.69	675.00						
0.5430	667.26	665.00							
0.47500	667.70	667.93							
9300	571.48 672.00	673.00							

CESAMIC = 40/1000, FOWER= 100 PER CENT

544.07 550.02 560.00 536.00 511.00 511.00  0.02 0.00 0.00 0.00 0.00 680.00  0.03 0.00 0.00 0.00 618.00  0.00 0.00 618.00  621.00	0.18
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	555.00
0.00 0.	2• 30
0.00 0.00 0.00	65.5
000000000000000000000000000000000000000	3.93
	00.00
521.00	3.99
	CC *3
	617.00
	614.00
	557.00

-131.43440 HTU/HR	
18	
FATE	
FLOW FATE	
FEAT	
THE TOTAL PEST	
1H (	

						Table 6 (continued)	Valve Temperature Profiles			
9•68	511.00	608.00	618.63				>			
0.63	511.00	611.90	613.71 613.23 612.81 613.43	608.00						
0.56	536, 33	611066	612,81	513,14						
Ģ• 20	569.03	612.53	613,23	614.97	619.00					
0.34	550,03	012.75	613.71	615.32 614.97	616.F2 619.00	618.00				
0 - 28	544.33	612.72	613.76	615,36	616.76	618.21	621.00			
91.0	5:5.13	613.03	612,53 613,76	615,38 615,36	616.66	617.97	619.27	617.00	614.00	557.00
00.0	588.00	514.111	614.57	61 5, 52	616.48	617,35	618,23	616.42	612,56	601.49
ISTINCE	2, 2003	5.0400	€060°¢	3.1703	0.240C	2,3100	Se 41 03	9.5500	C. 7203	0.9200

CESANIC = 40/1000, FOWER 78 SER CENT

DISTANCE	00.0	0.13	£.	7.34	0.50	0. 0. 0. 0. 0.	0.63	0,68
1.0764	250.00	557.00	503.00	454.00	481.0	485.00	490.00	490,00
Ø, C4 0 3	0.00	0000	00.0	00.0	0.00	00°0	0.00	651.00
0060-0	00 •0	0.00	0.00	00.0	00.0	00.00	0.0	661.00
0-1700	00.0	0.00	Û•01	0.00	0000	00-0	651.00	
0.2400	0.00	60.00	00.0	00 0	662.00			
00.31.00	00.0	7.00	0.00	663.00				
00100	00.00	3.39	661.03					
C. 5500	0.00	<b>662.00</b>						
0.7200	Ú0°G	669.00						
C. 5200	00.00	554.00						

THE TOTAL HEAT FLOW GATE IS -232.58849ETU/FR

						Table 6 (continued)	Valve lemperature Profiles			
0.68	450.00	651,00	90. 199			2	×			
0.63	490.00	652.85	658.32	651.00						
95.6	485-73	£45.45 649.73 657.12 650.47 hgm.90	653.42	656.28 656.95 EEEc.38 651.00						
1.59	491.00	650.47	552.15 653.14	656.95	662.00					
0.34	494.00	659.12	552.19		659.70 662.00	663.0C				
0.25	507.00 503.00	649.79	651.67 652.01	655.44	657.32 658.16	660.28	661.90			
0.13	567.00	646.49	651.67	654.99	657.32	02.559	££€6.51 661.90	662.00	667.99	554.00
00.00	520.00	645.41	651.36	654.32	656.51	65 F . 2 A	659.68	65 % 78	652.68	61 0.92
DISTANCE	00000	30 6400	000000	06 21 30	C+240¢	0.316.0	Co 4100	0.5500	0€729€	C. 9200

CERAMIC = 47/1000, POWER = 50 PER CENT

			U/HR	-120.05590BTU/HR	-120	TE 15	SAT FLOW 9A	THE TOTAL PEAT FLOW RATE IS
						567.00	0.00	3,5200
						\$57.00	9.00	0.7200
						267.00	00.00	6, 5500
					598.00	0.03	0.00	0.4100
				598.00	0.00	00 • 0	00.0	0+3100
			298.00	00.0	0.00	0.00	00 00	Co 2400
	58 &. 00	0° 20	0.00	00.00	00.0	00.00	0.00	0.1700
258.00	0000	00.0	0000	0.00	00 • 0	00 •0	00.00	000000
588.00	00.0	0000	0.0.0	0.00	0.00	0.03	00.0	00 00 ~0
529.00	525.00	638,00	638.00	538.00	633.00	527,00	Sr 9.00	0.00000
J. 68	0.63	9°86	7.53	0 • 34	0.25	e 1 °G	00°C	DISTANCE

						Table 6 (continued)	Valve Temperature Profiles			
9.69	529.00	588.00	558.00							
0.63	529.00	592.17	593.73	586.00						
0.56	635,00	592,24	593,11	593,21						
0.53	538.00	592.63	553.46	565.32	698663					
0.34	535.00	592.84 552.63 592.24	593.62 693.72 553.46 593.11	72 E54e87 595e03 555e24 5<5e32 E93e21 58£e00	555.89 596.19 596.71	558.00				
0.25	533.00	592.71	593.62	595.03	596 • 19	597.17 558.00	598.00			
0.18	537.00	592.73 592.71	693.55	E\$4.87	66.55	556.73	557.40	597.00	857.00	
00°C	619.00	592.95	59 7. 61	594.72	595.59	596.29	29.6.81	59 6. 33	593.57 557.00	
DISTANCE	0.0000	0 0 0 °C	0060-0	00210	66 +2 + 5	0.7100	5,4103	0.5500	0.7200	

574.66 567.00

CERAMIC = 40/1000, POWERE 25 PER CENT

0000	_	9-18	<b>3.25</b>	) • UA	53 در	J. 56	0.63	<b>0•</b> ¢3	
498.00		470,30	4/3.00	469.63	462.00	\$46.00	430.00	4 30 • 00	
0.00	e.	60.0	0.00	0.00	0.00	٥٥ °ر	00.0	609.00	
00.0	0	9.13	0.00	0.00	0.00	3,00	0	÷13°30	
00 •0	8	00 •0	0.00	0.00	0.00	0.00	00.809		
0000	و	2.30	0.00	0000	618.00				
0.00	ن و	00.0	00.0	618.00					
ن•ن	٤	00.0	610.00						
2.00		612,00							
00 •0		605.00							
0.00		582.00							

-229.314.30BTUZHR

THE TOTAL PEAT PLOW RATE IS

						Table 6 (continued)	Valve Temperature Profiles			
0• ée	4.30.30	608-00	618.00				Α			
0.63	430.00	605.47	612.18	00.809						
9° 56	446.00	605.55 606.52 677.68 637.84 605.47	6(6,99 617,56 618,61 619,89 511,29	612.29						
7.50	462.00	677.68	679.39	613.40	613.63					
9.34	469.00	606.52	678.61	610.42 511.54 613.40	639.96 611.06 612.37 614.96 613.C)	613.25 618.00				
0.25	473.00		617.56		612.37	613.25	610.00			
9.18	475.00	604.97	66.633	66.5.48	611.06	611.74	62 610,82	612.00	605.00	592.00
00.00	00 °8 54	604.73	696.34	69 8 2 8	96.669	61 0. es	610.62	617.12	603.35	588-17
DISTANCE	0.0000	60000	0066-1	C- 170G	C-240C	Cr 3100	0.4107	0.5500	C. 7200	0.9200

CERAMIC = 40/1000, POWER= 00 PER CENT

C	٥٠٠ ن	0.19	3.25	0.34	0.50	9.56	0.63	9• 68
	626.00	00.619	617.00	598.00	570.00	565.00	560.00	560.00
	00 00	0000	00.0	00.0	0.00	0.00	0 000	712,00
	00.0	0.00	00.0	0.00	0.00	00 0	00.00	722.00
	00.00	00.00	00.0	0.00	0.00	00.0	712,00	
	00.0	00 • 0	8	0.00	722.00			
	00.0	0.0	00.0	722.00				
	00.00	9	721.00					
_	0.00	720.00						
_	00.00	700.00						
	0.00	675.00						

-199-10940ETU/FR
2
RATE
FLOW
PEAT
TOTAL
THE

00.0	626.00	712.66	713.96	715.53	717.34	715,33	718.65	716.09	700-17
0.18	619.00	712.77		716,39	716.05		720.19	720.09	700.00
0.25	617.90	712.92	714,21 714,38	.93 716e39 716e75 717e28 717e77 716e40	34 716.05 718.67 719.77 722.00	719.33 727.19 722.00	721.00		
0.34	617.00 598.00	712.73	714.48	717.28	719.77	722.00			
7.5a	570.00		714.53	717.77	722.00				
3.56	570.00 565.00	712.54	714.78	716.40					
63.0	563,00	712.37 712.54 714.15	714.78 716.48	712.00					
O. 69	560.00	712.00	722.00			Table 6 (continued)	Valve Temperature Profiles		

682.26 675.00

0-9200

Temperature Profiles

CERANIC = 00/1000, POWER= 100 PER CENT

DISTANCE	00.00	3,10	0.25 0.25	0.34	3.50	98.0	0.63	0.68
0.000	563.00	655.0A	£58 <b>.03</b>	588.00	561.00	554,00	547.00	547.30
3. 2300	00.00	3.00	00.0	00.0	0.000	0.00	0000	665.00
0.0500	00.00	00.00	0.0	0.00	00.0	00.0	00.0	695.00
0.1300	00.00	0.03	00.0	0.00	0.00	00.0	685.00	
0. 20 CC	00.00	00 *0	60 • 0	00.00	697.00			
0.2700	٥٠٠ ن	0.00	٠٠٠٥	700.00				
Co 3700	0.00	00 00	705.00					
0015-0	00.0	655.00						
0.6800	2.00	685.00						
Co 3800	00 • 0	674.00						

-3197.26300 BTUZER
15
FLTE
FLOW
FEAT
TOTAL
Æ

DISTANCE	00° C	9.19	0.25	0.34	î. 59	9.56	0.63	0, 68	
رە <b>رد ئ</b>	563.09	655.00	558.09	559.00	558.00 559.00 561.00 554.00 547.09	554.00	547.09	547.00	
0000.0	56 3. 00	00*53%	£55.00 558.00	559.00	559.00 561.00	n 14 . 00	547.00	90° 589	
0.050.0	56.2.95	582.63	584.01	587.17	5P2.63 584.01 \$87.17 597.86 635.66 632.28 655.33	675, 66	632.2B	655.33	
2,1309	615.04	615+02	623.61	632-13	£15.02 623.61 632.13 652.60	662.57	685.00		
00620	640.83	647.46	647.46 654.76 667.91	667.51	697.00				
0.2700	661.63	670,99	561.63 679.39 630.92	799.09					Table 6 (continued)
0.3700	682.62	655.52	705.00						Valve Temperature Profil
0.5100	690.36	665590							
C) 6807	684.77	665.00							
0.9860	677.09	674.00							

CERAMIC # 09/1030 FOWER 75 PER CENT

DISTANCE	00.0	0.18	0. 25	0.34	0.50	0.56	0.63	0.68
00vċ*L	St 8.00	529.00	523.00	521.00	517.00	525.00	533.00	533.00
ñ. 000 a	0.00	0.00	0.00	00*0	0000	0000	0.00	650.90
0.0500	00.0	0.00	0.00	0.00	0.0	0.00	0	00- 699
0.1300	9.00	00.0	0.03	0.00	0000	0-0	650.00	
0.2900	00 00	0.00	00 • 0	0.0	667.00			
0.2700	00.0	0.00	0.00	67 5,00				
2.3700	0.00	0.00	675.00			!		
0.5100	0.0	676.00						
4.6800	0.0	652.00						
6. 2808	0.00	637.00						

-3118-67100ETU/FR THE TOTAL HEAT FLOW SATE 1S

DISTANCE	00.0	0.19	0.25	0.34	0.50	0.56	69.0	0.68	
0.0000	5.0.00	529.09	523.00	521.00	517.60	525, 50	532,00	£33.00	
0°00°0	548.00	£25.00	523.00	521,00	517.00	525.00	532.00	659.09	
0.0500	561.50	552.24	550.68	552,12	56 û e 1 1	573.64	663.72	000609	
9•1300	589.01	86.588	592.48 600.08	60000	619.00	626.54	650.00		
C.290C	61 3. 01	616.29	625.40	639,12	667.00				
0.2767	633.80	642.39	62.29	675.00					Tab
£e 3732	554.55	664.39	675.09						Valve
6.:100	663,33	670.00							
0.6660	652.42	652.03							
0000	641.43	637.00							

ible 6 (continued)
: Temperature Profiles

CEFAMIC = 30/1000, PLWEG = 25 PER CENT

557.00 561.	561, 13	551.00	563.00	567.00	365.00	564.00	564.00
		ن • ن ن	0.00	0	00.00		
00.0	0			•		0.00	534.09
3.00	60.	00.00	0.00	0	0000	00.0	544.00
00 °C	00	0.00	00.0	00.0	00.0	534.00	
0000	66.	0.00	0000	545.00			
00.00	90	9.00	546.00				
00.0	Ç.	544.00					
3.09 537	90						
0.09 526.	00						
0.00 515	00.						
	d or un	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	3.03 0.00 0.00 0.03 0.03 0.03 537.00 526.03	3.03 0.00 0.00 0.00 0.00 0.00 1.00 0.00 1.00 0.00 5.37.00 5.37.00	3.03 0.00 0.00 0.00 0.00 0.00 0.03 0.00 0.00 10.00 0.00 546.00 10.00 544.00 537.00 515.00	3.00       0.00       0.00       0.00         3.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         10.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00       0.00       0.00         0.00       0.00	0.00       0.00

TSTANCE	03.0	9118	0.25	9.34	1.50	3.56	0.63	<b>3. 68</b>	
06 06 0	560.09	561.00	561.00		567.00	365.00	563.00 567.00 365.00 564.00 564.00	564.00	
0.0000	560.Cn	661.00	561.00 561.00	563.00	567.09	565.00	564.00	534.10	
0-05-30	55.7.51	558.40	554.53		559.25 559.25		556,76 550.52 544.09	544.09	
0-1300	554,20	£ 5 4. 2 3	£54.23 554.00		553.47 549.83	545.01 534.00	534.00		
0002*0	16.038	556.77	553.36	549.31	545.03				
0016.3	54 7. 72	547.61	547.61 547.24 546.00	546.00					Table 6 (continued)
0042.0	543.31	543.60	544.00						Valve Temperature Profiles
0.5100	536.50	537.00							
C. 6800	526.71	526.00							
0.8800	518.36	£15.00							

CERAMIC = 00/1000 SOMER= 00 MER CENT

																		Table 6 (continued)	Valve lemperature Profiles			
0 • 68	514+00	580.00	2 90 • 00									<b>0</b> •68	514.00	580.00	253-00			;	Λ			
0.63	514.00	00.0	00.0	580.00								0.63	514.00	514.00	557.72	560.00						
0.56	£22.00	00.00	00 00	9.00								9.56	522,01	522.00	547,45	574.50						
0.51	530,30	00.0	٥٠٠٥	00.0	00.109						A + 1	9.50	530.77	530.00	547.29	575.36	6:11.00					
9.34	531,00	00.0	00.0	00.0	00.0	613.00					-1579.25307ETU/HR	₩ • G	531.00	531.00	546.60	570.56	551.55	613.90				
0.25	532.00	00 • 0	00.0	0.00	0.00	0.00	600.00				- 1579	2.28 8.28	532.00	532.00	547.63	568.46	584.23	596.43	600.00			
6.19	546.30	00.00	00.0	0.00	00.00	00.0	00 00	\$63.00	591.00	#E E. 00	7E 1S		546.00	546.00	55.0427	Ses. 10	E80+83	585.68	553.57	593.00	591-30	£55.00
00.0	58.9.00	00.00	( ) • 0	00.0	00 00	3.00	00.00	00.0	00.0	00 0	THE TOTAL PEAT FLOW RATE IS	0	588,03	59 A. DO	577.95	577,04	581.43	586.18	£8-33	584.52	565.93	56 3. 90
DISTANCE	4-9730	0964-5	000000	3, 1303	0° 5000	0.270A	C. 3700	0.5100	0.6800	C.9800	THE TOTAL	DISTANCE	6-1340	000000	0.750	00 1300	6.2000	0.2700	ودعناه	0.5100	C.6800	0068-0

NOTE THE LPPER LEFT MAND COPINER IS THE TOP CENTER OF THE PISTON OR VALVE. THE TOLERANCE FOR CHANGE IN AVG ELEMENT TEMP BETWEEN ITERATIONS IS THE THEETANCE FOR MAXIMUM CHANGE IN TEMPERATURE IS 3, 19303 THE THERMAL CONDUCTIVITY FOR THE INSULATION IS 0.4000 THE THERMAL CONDUCTIVITY FOR THE WETAL IS 33.00030

0.10000

Valve Temperature Profiles Table 6 (continued)

CERAMIC = 10071033, CONFE 100 FER CENT

	540.00 537.00 520.00 511.00 562.00 578.00 606.00 548.00 500.00	500.00	0001 541000	0.10 231.00	0.00 220.00	0.00 195.00	0.00 136.83
30.1	2 d 4 d					000	268,30
1 • 00	606.03	0000		ž			กกกกกกก
0.75	578.30	0.00	00.0	308.00			กกกกากกก
0.00 0.11 1.75 A.38 1.50 0.75	562.00	0.00	00.0	378.00	การการการกา		הררחמהרו
1,38	641.00	00.00	00°0	327.03	<b>กากวาก</b> กา		, , , , ,
3.25	520.00	0.00 0.00	00.0	339.00	ດດດຸດດຸດດຸດ		nnnnnn
0.41	534.00	0.07	00.0	317.03	ררנונחחר		0000000
00.0	540.00	60°0	0.00	311.00	POPERS CONTRACTOR CONT	SECTION OF THE PARTY.	268-30 CONDUNATION OF THE TOTAL
30W.1510	3,110;	5061.5	0.2900	654700	59150	1.1500	

THE TOTAL PEAT FLOW RATE IS

736 .44050BTU/HR

	1, 60	500.00	41.00	231.00	000		195.00
•	1.50	548.00 500.00 5	313e14 312a58 311.ck 21. ro	241.98 2	234.81	7 10115	264.00 183.58 136.80
č	C • 1	548.00	281-14	311 00 23 274.99 241.98 308.69 296.93 274.99 241.98	. 18.00 309.00 307.00 308.00 30.500 298.00 273.00 234.81	20.00	264.00
09-1	530.00 520.00 541.00 54.00	000000	33.3° 88	296.93	298.00	חמחרנים	n manna
9.75		00000	C	308,69	305.00	กกกากกก	กกกลกกกา
0.50	242	2000		700110	308.00	ກລາດດາ ດກ	ລາດດດາກກ
0.38	541.00	317-11	311.66		307.00	LUUUUUUUU	ากกกกกก
0.25	520.00	317.24	312.53		309.00	<b>ກ</b> ດດກດດລດ	นบบบบบบบ
0,11	530,00	316.02	313,14		310.00	مدددمممه	าเกลา กาล
00.0	540.00	318.53	313,36			מההמדמדמת חדר המתחמת המתחת המתחת המתחת המתחת המתחת המתחת המתחת המתחת המחדר מחוד ביצור ביצור ביצור ביצור ביצור ה	กมากการเราะเราะบายการการการการการการการการการการการการการก
DISTANCE	0.0000	0001*0	Jo 2900	9.4700	i i	2-5160	1.1590

13 THE MINEG OF ITERATIONS NAS

Piston Temperature Profiles Table 7

CEGAMIC = 100/1000, POWERE 75 PER CENT

DISTANCE	0.00	0.11	) • 25	7,38	9.11 3.25 7.38 7.55 0.7° 1.00 1.25	0,7	00° 2	1,25	1.59	1.63
	622.00	547.99	472.03	47 - 00	622.00 547.00 472.03 475.00 477.00 568.00 516.00 500.00 455.00	568.00	516.00	500.00	495.00	
	0.00	00.00	00.0	00.0	(0°0 00°0 00°C 66°U	00.00	00.00	0.00	0.0	0.00 221.23
	00.00	0.0 °C	0000		0.00 0.00	00°0	00.0	00.0	0.00	0.00 210.00
	27 4. 00	273,00	272.00	270,00	274.00 273.00 272.00 270.00 270.00 271.00 271.00 251.50	271.00	271.00	251.00	00.0	0.00 198.00
5	กษายายาย	บบบบบบบบ	บบบบเบบบ	กากากกก	<b>ԾՄՍՄԱՍԱՄԱՄՄՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍՍ</b>	ירטיגיטטטי	nnnnnn	241.00	00.00	0.30 175.03
5	ເນນບບບບບບ	Luctobou	იიიიიიიი	กกกกกกกา	บขบบขบบนประเทศ	וטטטטטטווג	กดากกากก	241.00	00 00	0.00 128.00

THE 1-TAL PEAT FLOW RATE IS 705,79390 ETUZ-PR

CISTANCE	0		,							
		1100	0.25	0.38	0.10 0.25 0.38 0.50 0.75 1.00 1.25 1.50 1.60	0.75	00• 1	1.25	1.50	1.60
0.000.0	622.00	547.03	472.00	475.00	622.00 547.00 472.00 475.00 477.00 568.00 516.00 500.00 ACE.ON ACE.ON	568.00	516.00	500,00	40.80	
÷0€110€	284.63	2 62.49	279.83	279.20	284.63 262.49 279.83 279.20 278.86 280.37 273.25 254.18 225.49 279.40	280,37	273425	400	9 4 6	00.00
.2900	276.80	276.40	275.46	274.68	276.80 276.40 275.46 274.68 274.29 273.74 267.66 249.53 110 110 110 110 110 110 110 110 110 11	273.74	267.66		000	00-122
C. 4700	274,00	273.00	272.03	270.00	274.00 273.00 272.03 270.00 270.00 270.00 271.00 271.00 271.00 272.00 270.00	271.00	24.	20.00	4 • V	219.30
0.0160	Characteristics						06.112	251.09	211.76	198,00
	COCCOCOCACECECO DO COCECE CE COCECE C	,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	ດດດດດດດດ	ונרחרונה	กดกดกกกก	าะเยบบบบ	nnnnnn	541 •0 ņ	190.60	175.00
1-1500	บอบของของของ ของขณะเสมของเขา เมื่อของของของของเขา เล่า เมื่อ 167.68 128.00	UULUUUUL	บบบบบบบ	<i>กภกกกกก</i> า	เลกาทกกกก	กกกกกกกก	מבמרביות	241.00	167.68	128.00

THE NUMEER OF ITERATIONS MAS 19

Table 7 (continued)
Piston Temperature Profiles

CERAMIC = 100/1000, FOWER= 59 PER CENT

DISTANCE	00°0	0.11	0.25	0.38	0.00 0.11 0.25 0.38 0.50 0.75 1.00 1.25 1.50 1.60	0.75	1 • 00	1.25	1.50	1.60
000000	48.3.00	481,00	478.Ng	479.00	483.00 481.00 478.00 479.00 479.00 484.00 480.00 481.00 478.00 470.00	484.00	480.00	481.00	478.00	473.00
Go 1000	00 •0	იი აე	0.03	0.00	0.00 C.70 7.03 0.03 0.19 5.00 0.00 5.00 0.00 186.00	00.00	0.00	00.0	0.00	186.00
0062.0	0.00	0.0	00 • c	00.0	0000 0000 0000 0000 0000 0000 0000 0000 0000	00.0	00.0	00.0	00 00	181.03
6-4-63	217.00	216,33	216.00	216.00	217.00 216.00 216.00 216.00 217.00 218.00 22C.00 200.00	218,00	226.00	200.00	0.00	0.00 175.00
0-5160	กษณ์มายขอยสมาย เกษายายายายายายายายายายายายายายายายายายาย	מפרנמממר	กกกกกกก	กากาากกา	กากกกากก	กากกากกก	กกากกากก	190 •00	0.00	0.00 164.00
1.1500	บบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบ	วกกาวกก	บบบบบบบ	าาดกกกกา	กกกกกากก	กกกกกกกา	OOOLUOO	1 90 • 00		0.00 116.00

THE TOTAL PEAT PLOW RATE IS 792.869808TUZHR

DISTANCE	0000	0.11	0.25	3.38	0.11 0.25 0.38 0.50		3.75 1.90 1.25 1.50	1. 25	1.50	1 . 60
0.000.0	483.00	461.00	478.00	479.00	479.00	484.00	483.00 4E1.00 478.00 479.00 479.00 484.00 480.00 481.00 478.00 478.00	481.00	478.00	478.00
0001.0	227.66	227.49	227.46	227.59	227. 78	227.56	227.66 227.49 227.46 227.59 227.78 227.56 224.17 239.71 193.70 186.30	239.71	193, 70	186.30
0062°0	221072	221.65	221.69	221.80	221.59	221.65	221.73 221.65 221.69 221.80 221.59 221.65 218.28 203.46 187.15 181.00	203.46	187.15	181.00
0.4700	21 7.00	216.00	216.00	216.00	217.00	218.00	217.00 21f.00 216.00 216.00 217.nr 219.ng 220.00 200.09 181.62 175.03	2 00 • 00 5	181.62	175.00
7,9163	UNDUTERURAL L. LOUDUNGUUNGUUNGULUNDURUNGUNUNGUNUNGUNGUNULLUN 199.30 168.44 164.00	מנברממממ	ດດດກຸກດດດ	กกลกกกกา	กกกกกกกก	กกก <b>กก</b> กกก	חחחרוחח	199.30	168.44	164.00
161502		רררהממר	กกกกกกกก	וחחווווו	กกกกกกก	กากกกกกก	nnnnnn	190.00	145.46	116.00

THE NUMBER OF ITERATIONS NAS 19

Table 7 (continued)
Piston Temperature Profiles

CERAMIC = 100/1000, POWER= 25 PER CENT

DISTANCE	00.0	11.0	0.25	0.38	0.00 3.11 0.25 0.38 0.53 0.75 1.00 1.25 1.50 1.60	0.75	1.00	1, 25	1.50	1.60	
200000	538.00	597.93	475.00	480.00	538.00 597.99 475.00 480.00 484.00 476.00 475.00 475.00 475.00 475.00	476.00	475.00	476.00	475.00	475.00	
0.1000	0.00	0.00	00 • 0	00.0	00*00 00*00 00*00 00*00 00*00 00*00 00*00 00*00	0,00	00.00	00.0	0000	167.00	
2. 2900	00.00	0.00 0.00 0.00	0.00	0.00	0.30	2.00	00-00 00-00	00.0	00.0	0.00 163.00	
0.4700	196.00	15€.00	195.00	154.00	196.00 195.00 195.00 154.00 195.00 196.00 196.00 176.00	196.00	196.00	176.00	0.0	0.00 159.00	
09 15 0	กษณาแนนมายะเบาบานมามามามามามามามามามามามามามามามามาม	חבררחחחח	กกกกกกกก	LUUUUUUUU	ກດດກດກດດ	กกกากกากก	ດດາດດາດດ	166.00	00.00	0.00 151.00	
1.1500	00000000000000000000000000000000000000	ההרוחחחו	กกกกกราก	ບບບບບບບ	ากกกกกกก	าบบบบบบบบ	UWUWU	166.00	0.00	118.00	

THE TOTAL HEAT FLOW RATE IS 740.26390BTU/FR

DISTANCE	00-0	11.0	90.0	6		ì				
	1	•		900	00.00	67.0	0.50 0.50 0.50 0.50 1.50 1.50	1.25	1.50	1.60
7,0000	538.00	507.00	475.00	480.00	484.00	476.00	538.00 507.00 475.00 480.00 484.00 476.00 475.00 475.00 475.00 475.00	476.00	4 75.00	475.00
6061.0	20 9. 71	207.78	296.89	206.70	206.90	205,87	208.71 207.78 296.89 206.70 206.90 205.97 201.77 188.05 175.35 167.00	188.05	175,35	167.00
0.2400	201.08	200.83	200.63	200-40	230.42	199.65	201.08 2r0.89 200.63 200.40 200.42 199.65 195.48 181.42 168.45 163.00	181.42	168.45	163.00
004400	196.40	155.00	195.09	194.00	195.00	196.30	196.UO 155.00 195.00 194.00 195.00 196.00 175.00 175.00 163.62 155.00	176.00	163.62	155.00
0,9160	UNUVALUAVULEELUVULEUVUVEUVULEULEELEVUVUVULEUVUVUVUV	וררוחתחו	UNDULUUN	กาาวกกกา	UUUUUUUU	การเการ์	กกกกกกก	166.00	153,38	151.00
1-1590	บนเมาเพิ่มเนยนะเบยยะเนนเยยยยยยยยยยยยยยยยยยยยยยยยยย	חחרוחחחר	UUCUUUUU	ເບບບບບບບ	กบบบบบบ	กรถ.งกถล	annanna	1 66,03	137.52	118.33

THE NUMBER OF ITERATIONS NAS 19

CERAMIC = 100/1000 + POWER= 0 PER CENT

1.60	475.00	146.00	0.00 142.00	0.00 138.00	0.00 130.00	115,30
0.75 1.00 1.25 1.50	476.30 175.80 475.80	0.00 146.00	00.0	0.00	0.00	0.00 115,30
1.25	476.30	0 • 0	00.0	156.00	146.00	146.00
1 • 00	454.00 490.00 486.00 481.00 476.00 476.00	0000	00.0	177.00 176.00 176.00 175.00 176.00 177.00 176.00	กดกกกกก	ກກາກກາ
0.75	476.00	0.00	00.0	177.00	กกกกกกกก	ກຸກກາກກຸກ
0.50	481.30	00.00	0.00	176.00	ากกกกกกก	ກາກກາກກ
0.11 0.25 0.38	486.00	0.00	0.00	175.00	กาากกกกา	กกกกกกกา
0,25	490.09	00-0 00-0	00.0	176.00	บบบบบบบบ	กกกากกกกก
0.11	454.00	00.00	00.0	176.00	ררורחחחר	ממררמחממ
00.0	497.00	00.00	Ŭ0 <b>•</b> 0	177.00	กษายายายายายายายายายายายายายายายายายายาย	00*9% 1 กรรกกกกกกกกกกกกกกกกกกกกกกกกกกกกกกกกก
DISTANCE	uacora	03(1.00	0.2900	0.4700	0-5160	1.1500

785.2185081U/HR

THE TOTAL HEAT PLOW RATE IS

BISTANCE	00.0	0.00		0.25 0.3E		2.75	3.50 3.75 1.00 1.25 1.50	1.25	08.01	9
0 0 00 00	497.00	454 00	4 90.00	486.00	431.00	476.00	497.00 454.00 490.00 486.00 481.00 476.00 476.00 476.00 475.00 475.00	476.00	475.00	475.00
v001.	199.48	185.26	189.00	198.64	188.44	187.40	199.48 185.26 189.00 198.64 188.44 187.40 182.74 168.66 155.26 146.00	168.66	155.26	146.00
C. 2900	182,36	192,24	182.07	191.79	181.71	180.76	182.36 192.24 182.07 191.79 181.71 180.76 175.99 161.59 147.89 142.00	161.59	147.89	142.00
0.4700	177.00	176.00	176.09	175.00	176.00	177.00	177.00 176.00 176.09 175.00 176.00 177.00 176.00 156.00 142.99 138.09	156.00	142,99	138°00
0, 51 67	00°06' 33°6' 133°60' 1	וממר רממממ	เพียนบบบบน	LUUUUUUU	กกกกกกกก	יזטטטריטטי	กกกกกกก	146.30	133,82	130.00
1-1500	ายอยายายยายยายยายยายยายยายยายยายยายยายยา	ากกกากากเ	กกกากกกก	רחמררחמם	กกกกกกกก	กกกกกกกก	იიიიიიი	146.00	126.39	115.00

THE NUMBER OF ITERATIONS BAS 19

Table 7 (continued)
Piston Temperature Profiles

CEGAMIC = 70/1000, POWERE 107 PER CENT

DISTANCE	00.0	0.11	0.25	9.38	0-00 0-11 0-25 0-38 0-50	0.75	00 • 1	1,25	1.50	1.60
000000	533.00	532.00	530.00	528.00	533.00 532.00 530.00 528.00 527.00 533.00 527.00 525.00 527.00	533,00	527.00	525.00	527.00	527.00
0.0700	00° C	0.00	0.00	00.0	0.00 0.00 0.00 0.00	3.00	0000	0000	00.00	0.00 264.00
0.2600	00°C	0.00	00.00	0000	0.00	00.0	0000	0000	000	250.00
00 44 00	319.00	316.00	317.00	316.00	319.00 316.00 317.00 316.00 317.00 318.00 318.00	318.00	318.00	298.00	0.0	236,00
0.8960	นษณะคนหนานยา แบบบนบนบนบน เล่นนาม เล่นนามของของของของของของของของของของของของของข	กกกาากก	กลากกากก	ດດດກດດດາ	ທຸດທຸດທຸດທຸດ	กกกกกกกก	กกากกก	288.00	800	0.00 207.30
1. 1200	ปษณ์เป็นมีเป็นเป็น และเก็บเป็นของเมื่อของเมื่อ เป็นเป็น เป็นเป็นเป็นเป็นเป็นเป็น 288,00	חבררחחחה	กดกกกกก	ບບບບບບບ	กราบเลยายน	กกกกกกก	ດດາດດາດ	288,00		142,00

THE TOTAL PEAT FLOW RATE IS 888-24020ETU/FR

DISTANCE	00.0	0.11	0.00 0.11 0.25 0.38	0.38	0.50		0.75 1.00 1.25 1.50	1.25	1 •50	1.60
000000	533.00	532,09	530.00	528,09	532.00 530.00 528.00 527.00 533.00 527.00 525.00 527.00 527.00	533,00	527.00	525.00	527,00	527.00
002000	330,06	325, 91	329.46	329.04	330e06 325e91 329e46 329e04 328e38 327e91 321e87 302e26 269e82 264e0n	327.91	321.87	302.26	269.82	264-00
0.2600	323.42	323,28	322.86	322,50	323.42 323.28 322.86 322.50 322.30 321.16 315.12 294.94 261.35 250.00	321.16	315.12	294.94	261.35	250.00
0.44.00	319.00	318.00	317.00	316.00	319.00 318.00 317.00 316.00 317.00 318.00 318.00 258.00 258.00	318,00	318.00	258-00	. C. C. R. C.	9 9 6
0.8860	00000000000000000000000000000000000000	חרווחחחח	מחחחחחח	ากกากกกา	กากกกกกก	กากกรากกา	nnnnnn	288.00	225.66	207.00
1-1200	WUWUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU	กกกาวกก	ດດດດດດດດ	กลากกกกก	บางการเก	กบบบบบบบบ	מטטרטטט	288.00	194-12	142,30

THE NUMBER OF ITERATIONS BAS 20

CERAMIC = 73/1000, FOWER= 75 PEF CENT

DISTANCE	00.0	0.11	ñ. 25	0.38	0.00 0.11 0.25 0.38 0.50 0.75	0.75	00	1.25	1.00 1.25 1.50	1.60
0000	532.00	549.00	547.09	566.00	532.00 549.00 547.00 566.00 594.00 514.00 515.00 514.00 516.00 516.00	514.00	515.00	514.00	516.00	516.00
9,0700	00.00	0.00 0.33 0.03	0.00	00.0	00.0	00.00 00.00	0.00	00°C	00.00	0.00 234.00
0.2600	0.00	0.00	00.00 00.00	0.00	0.00	0.00	00.00	0000	00.0	0.00 221.00
00 * * * 0	285.00	284.00	284.00	283.00	285.00 284.00 284.00 283.00 283.00 283.00 284.00 264.00	283.50	284.00	264.00	0.00	0.00 209.00
0.8860	ษษยยยยยยยยยยยา เมลา เมลา เมลา เมลา เมลา เมลา เมลา เมล	חרווחחרו	იიიიიიიი	กกกกกกกก	กากกกกกก	กากกากกาก	000000	254 .90	00.0	0.00 183.00
1,1200	นษณะของของจาก เกษาวัน เพลายายายายายายายายายายายายายายายายายายาย	กรรรากก	บบบบบบบบ	いいいいいいいい	กาดกกกก	ກດກາດກາດກ	ากการกา	254.00		0.00 138.00

THE TOTAL PEAT FLOW RATE IS 980-19750BTU/HR

1.60

1.50

1.25

1.00

514.00

9.59 584.00

0.38 566.00

547.00

0.11

532.00

D15T#NCS 0.0000

0- 2700	298.98	259.39	299 • 20	299.49	259.60	294.79	298.98 259.09 299.20 259.49 259.60 294.79 285.47 270.77 241.01 234.00	270.77	241.01	234.00
0-2600	291.25	251017	291.05	290.72	250.24	287.58	291.25 251.17 291.05 290.72 250.24 287.58 282.05 262.77 231.96 221.00	262,77	231.96	221.00
06.400	295.00	264.00	284.00	293.00	283. C 0	283.00	285.00 284.00 284.00 283.00 283.fg 283.00 284.00 264.00 223.32 209.30	264.00	223,32	209-30
C. 8860	เลยมะบบบบะบบเลยนายบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบ	חחווחחחו	กกกกกกกก	กกกกกกกา	บบาบบนาบบ	<b>DODODOO</b>	กกากกก	254.00	200-19	183.00
1,1200	00000000000000000000000000000000000000	המרניממר	กกกกกกกก	רשמממממרי	ひひひひないこと	იიიიიიი	חחחחחח	254 000	178.11	138.00

THE NUMBER OF ITERATIONS WAS

Table 7 (continued) Piston Temperature Profiles

CERAMIC = 70/1600, POWER= 50 PER CENT

8	0.00 0.11 0.25 0.38 7.50 0.75	1.50	0.75	8•1	1. 25	1.50	
2 E. 00	520.00	532.00	528.00	522.00	522.00	521.00	521.09
0.00	3.00 0.00 0.00		00.00 00.00 00.00	00.00		00.00 00.00	204.30
00.00 00.00	00.00 00.00	00.0	0000	0000	0000	0.0	0.00 194.00
24E+00 24	245.00 245.00 244.00 244.00 245.00 245.00	244.00	245.00	245.00	225.00	0.00	183.00
ກວດດດດດດດດດ	กการสายการการการการการการการการการการการการการก	ภากกกกกา	านนานนาน	ດຕາດດດ	215.00	000	162.00
ירנטטטרטטטטי.	UUMUUUULLI LUUULUUUUUUUULUULULUULUUUUUUUUUU	ลกภกกการ	<b>ก</b> กกกกกกก	ດດາດດາດ	215.00	0.00	135.00

THE TOTAL PEAT FLOW RATE IS 1082-126008TU/PR

CISTANCE	0	9.11	0.25	0 - 38	9.11 0.25 0.38 0.50 0.75 1.00 1.25 1.50 1.60	0.75	8 .	1.25	1.50	1.60
000000	520.00	526.00	535.49	533.00	520.00 528.00 535.79 533.00 532.00 528.00 522.00 522.00 521.00 521.00	528.00	522.00	522.00	521.00	521.00
0.0700	261.50	261.61	261.67	261.20	261.50 261.61 261.67 261.20 250.79 259.46 254.14 237.19 213.28 204.00	259.46	254.14	237.19	213.28	204.00
0.2500	252.94	252.85	252+68	252.26	252.94 252.85 252.68 252.26 251.87 250.63 245.33 227.82 203.16 194.00	250.63	245,33	227.82	203.16	194.00
C. 4400	246.00	245,00	245.19	244.00	246.00 245.00 245.07 244.00 244.07 245.00 245.00 225.00 194.31 183.00	245.00	245.00	225.00	194.31	183,00
6.8860	บบบบบบบเขาขอยเขยยยยยยยยยยยยยยยยยยยยยยยยยยยยยยยย	กกกากกก	บบบบบบบ	ากกกกกก	กากกากกาก	กกกกกกกก	ממתרממ	215.00	175.41	162.00
1.1209	UUUVUUUUVUUUVUUUVUUUVUUUVUUVUUVUUVUUUVUUUU	מבררתתחר	บบบบบบบบ	กากกกกภา	מחחחחם	UUUUUUU	UUUUUUU	215.00	161.91	135,00

THE NUMBER OF ITERATIONS WAS 19

Table 7 (continued) Piston Temperature Profiles

CERAMIC = 70/1000, POWER= 25 PER CENT

99.	r		175.00			119.00
1.50		00.0	00.0	0000	00.0	00 %
1.25	560.00	00.0	000	195.00	185.00	185.00
0.75 1.00	565.00 568.00 562.00 560.00	0000	00.0	215.00 214.00 214.00 213.00 213.00 214.00 215.00 195.00	กกกากกก	ממתרמת
0.75	568.00	00.00	00 00	214.00	<b>CONTRACTOR</b>	ົວກາກກາລາກ
09 • 6	565.00	0000	0.00	213.00	กากกกกกก	ลกคากกก
0 38	550.00	00.00	00.0	213.00	ากกกกกกา	กรกกกกกกา
0.25	568.00 551.00 534.00	00 • 0	00.0	214.00	กกกกระกาก	บบเบบบบบ
3.11	551.00	00 •0	0.00	214.00	חרריתחתר	חחררתחחרי
00•0	568.00	00 •0	<b>0°0</b>	21 5. 00	00° 58 2 กกกากกากกากกากกากกากกากกากกากกากกากกากก	0 0 * 3 8 1   กกภาคกกคกคกคกคกคกคกคกคกคกคกคกคกคกคกคกคกค
DISTANCE	<b>9</b> •0000	9.0700	٥٠52-٥	00 44 00	0.5860	1.1200

THE TOTAL PEAT FLOW FATE 15 1283-71900BTU/HR

	6001		26.00			00-101
4	000	F 1 40 -	183,10	174.70	A 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4	143.18
20.41	560 20	213.59	202.20	00.60	185-00	185.99
1 . 00	## 1.00 534.00 550.00 #655.00 568.00 562.00 550.00 534.00	233.91 233.06 233.38 233.76 233.15 226.88 213.59 165.13 183.00	223-39 223-16 222-56 222-86 222-14 217-92 202-20 183-19 176-00	215.00 214.00 214.00 213.00 213.00 214.00 215.00 155.00 174.78 174.78	חתתתתתת	מממר ממים
9.75	568.00	233,15	222.14	214.00	บบบบบบบบ	กกกกกกกก
0.50	£65.00	233.76	222.86	213.00	שטישנישמ	มากกากส
0.25 0.38	550.00	233,38	222.56	213.00	ורמחחחחחו	רטטטרטטיי
0.25	534.00	233.06	223,16	214.00	ากวาทกากกา	າກາກກາກກາ
0.11	SE 1.00	233.91	223, 38	214.00	ากคลาวกก	ורררחחחר
00 • 0	568.00	234,55	22 3, 54	215.00	รัฐการการการการการการการการการการการการการก	บบั•611 81•E+1 บับ•81 กณากถกกกกกกกกกกกกกกกกกกกกกกกกกกกกกกกกกก
DISTANCE	000000	00100	0,2606	0.4.0.	29 5 9 C	1,1200

THE MUMBER OF ITERATIONS NAS 19

Table 7 (continued) Piston Temperature Profiles

CERAMIC = 70/1000, PHWERE A FER CENT

0000	0.00 0.11 3,25 3.38 7.59 9.75 1.00 1.25 1.50 1.69	3,25	0.38	7.53	C 1	1.00	10.25	1.50	1.69
6	3.09 0.09 3.00 0.00 0.00 0.00 0.00 0.00	00.00	00.100	00.000	00.00	565.00 0.00	266.00	565.00	156.00
00	0.00 0.00 0.00 0.00 0.00 0.00	0.00	00 •0	0000	00.00	0000	00.0	00.0	0.00 151 00.0
8	177.00 176.00 176.00 175.00 175.00 176.00 176.00 156.00	176,00	175.00	175.00	176.00	176.00	156.00		0.00 146.00
ฐ	UNDUBUSUBLE(UNDUBUSUSUSUSUSUSUSUSUSUSUSUSUSUSUSUSUSUSU	იიიიიიიი	LUUUUUUU	שטטטניניט	ດດ <mark>ດດດກ</mark> ຄວດ	OUULUUU	146.00		0.00 136.02
2	UNIONUUUULLILLUUULLUUULLUUULLUUULLUUUUUUUUUU	ממתר במת	ורמתמתחתר	าวกกกรรก	NO O O O O O	UUUUUUU	146.00		0.00 114.00

THE TOTAL PEAT FLOW RATE IS 1395-23900BTUZHR

DISTANCE	00.0	:: C	0+00 0+1: 0+2E 0+3B 7+50 0+75 1+00 1+25 1+50	0.38	9.50	0,75	1 • 00	1.25	1.50	1.60
2,000,0	522.00	542.00	522.00 542.00 562.00 561.00 560.00 575.00 566.00 566.00 565.00 565.00	561.00	560.00	575.00	566.00	566.00	565,00	565.30
00100	107.38	197.54	197.38 157.54 158.55 198.23 157.98 197.90 193.70 130.71 170.09 156.00	198.23	197.98	197.90	193.70	1 30 . 7 1	170.09	156.00
2,7600	196•66	186.63	186.66 1PC.63 186.62 186.29 186.76 185.49 181.45 169.03 157.10 151.00	186+29	186.76	165.49	18 1. 4€	168,03	157.10	151-00
Cc 44 00	177.30	176.00	177.30 176.03 176.03 175.00 175.00 176.00 176.00 156.00 149.30 146.00	175.00	175.00	176.00	176.00	156.00	149.30	146.00
0.88.0	ODDINGO DO TOTAL DO TOTAL DO TOTAL LO TOTAL DO T	იიიიიიიი	UN JURUNU	ากกกกกกา	ากกากากก	იიიიიიიი	0001000	146.03	137.91	136.00
1, 1293	บบนั้นขับขับบันตะแบบกายขอยบันต์แบบบันตับขับบันตับขับบันตับขับบันตับขับบันตับขับบันตัด 146.00 127.11 114.00	עכבנטטייט	nnnnnnn	กกกกกกกา	กกกกกกกก	กกกากกา	იიიიიიი	146.00	127.11	114.00

THE NUMBER OF ITERATIONS MAS 19

CERAMIC = 40/1000, POWER= 100 PER CENT

PISTANCE	0.00	0.11	9.25	9.38	0.00 0.11 3.25 9.38 0.50 0.75 1.00 1.25 1.50 1.60	0.75	00.1	1.25	1.50	1.60
0° 00 -0	524.00	521,33	517.00	518.00	524.00 521.3) 517.0) 518.00 518.00 503.00 495.00 510.00 510.00 510.00	503,00	495.00	510.00	510.00	510,00
0-040-0	00•0	00 00	00.00	0.00	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 286.00	00.0	0.00	0.00	0.00	286.00
0،2300	0.00	0000 0000 0000 0000	00.0	0.00	0000	00 0 0 00 0		00.00		0.00 269.00
Co 4100	316,00	315,00	313.00	311.00	316.00 315.00 313.00 311.00 312.00 313.00 315.00 295.00	313,02	315.00	295.00	00.0	0.00 252.00
0.8560	กษณะเลยแบบเกาะเลยเลยเลยเลยเลยเลยเลยเลยเลยเลยเลยเลยเลยเ	חבררכחר	רתחתרתתת	ลาลดดดดา	กาดกกกกก	<b>ດ</b> ກດດດດດດ	กกากกกก	285.00	0.00	0.00 217.00
1.9360	งของเราะยนต้อยเลยสมาชิงของของของของของของของของของของของของของ	<mark>กดก</mark> เคกกณ	იიიიიიიი	<u> </u>	กาดกกกก	<b>ດທຸດຄຸດຄຸດ</b> ຄ	חחחחחחח	285.00		0.00 131.00

THE TOTAL PEAT FLOW RATE IS 1320.81300BTUZHR

DISTANCE	00.0	0.00 0.11		0.25 0.38	1.50	9.75	1 • 00	1.25	1.00 1.25 1.50	1.60
000000	524.00	521.00	517.00	518.00	521.00 517.00 518.00 518.00 5n3.00 495.00 510.00 510.00	£ n3 • 00	495.00	510.00	510.00	510.00
0° 3400	334+30	333.94	332.98	332.41	334.30 333.94 332.98 332.41 332.15 330.33 326.05 311.42 289.40 286.03	330,33	326.05	311.43	285.40	286,00
C. 2300	323.42	323, 1.8	322.39	321.72	323.42 323.18 322.39 321.72 321.49 320.38 316.32 300.00 276.65 269.00	320.38	316,32	300.00	276.69	269.00
0.4100	316.00	315.00	313.00	311.00	316.00 315.00 313.00 311.00 312.00 313.00 315.00 255.00 263.37 252.00	313,70	315.00	255.00	263.37	252.30
0, 4563	UNCJULUTUUULL VIJULUUVUUUUULUUUUUUUUUUUUUUUUUUUUUUUUUU	חחרו חחחר	ດດດດດດດດ	LUVUUUUU	บบบบบบบบ	าชบนเรายนา	nnnnnn	285.09	221.05	217.03
1,0300	<b>บนบนบบชนะบนธนะเบบบนนบบบบบบนนนะเนะเนนนนบบบบบบบบนบนบนบบบบบบบบ</b>	רמרנמממת	nnnnnnn	רחחורוחו	ນດດ ດດດດດດ	וחחחרתחחו	กกกากกก	285.00	190.67	131.00

THE NUMBER OF ITERATIONS NAS 20

Table 7 (continued) Piston Temperature Profiles

CFRAMIC = AOZIGNO, POWER= 75 PER CENT

DISTANCE	00.00	0.11	9.25	0.38	0.00 0.11 0.25 0.38 0.59 0.75 1.00 1.25 1.50	0.75	00 • 1	1.25	1.50	1.60
0 0 0 0 • 0	515.00	205.00	502.00	002.00	515.00 505.00 502.00 305.00 508.00 505.00 515.00 505.00 508.00	505.00	515.00	505.00	508.00	508.00
0.0400	00.0		00.0	00.0	0000 0000 0000 0000 0000 0000	0-00	0000	00 • 0	0000	0.00 243.00
Co 2300	00.0		00 00 00 00	00.0	00.0	00-0	0.00	00.0	00 00	0.00 227.00
001700	259.00	256.00	258.00	258.00	259.00 258.00 258.00 258.00 258.00 259.00 259.00 239.00	259.00	259.00	239.00	0.00	0.00 211.00
C. 8560	หายอยายอยายอยายอยายอยายอยายอยายอยายอยายอ	ກ ກາກກາ <b>ກກ</b>	กควากวากก	เบษบบบบบ	บบบบบบบบ	วกกกกกกา	ითიიიი	229.00	0000	0.00 179.00
1.0800	กบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบ	רפרנחחחה	กกกากกกก	וחרחתהה	กลดดดดดก	<b>ก</b> กกกกกก	nannann	229.00	0.00	0.00 123.00

THE TOTAL PEAT FLOW RATE IS

1618-87500ETU/FR

DISTANCE	00.0	0.11	0.25	0.38	0.00 0.11 0.25 0.38 0.53	0.75	1.00	1.00 1.25 1.50 1.60	1.50	1.60
0900-0	515.00	208*00	502.00	505.00	515.00 509.00 502.00 505.00 508.00 505.00 515.00 505.00 508.00 508.00	505.00	515.00	505.00	5 0 E. 0 O	508.00
0.0400	283.49	263.09	282.60	282.71	283.49 2E3.09 282.60 282.71 282.75 281.83 278.73 263.58 247.97 243.00	281.83	278.73	263,58	247.97	243.00
0.2300	279.29	270.09	269.97	269.51	277.29 270.39 269.97 269.51 269.78 268.58 264.85 249.68 233.00 227.00	268,58	264.89	249.68	233,00	227.00
C. 4100	259.00	258.00	258.07	258.00	259.00 258.00 258.07 258.00 258.39 259.00 255.00 239.00 218.90 211.00	259.00	255.00	239.00	218.90	211.00
0.4560	<u> </u>	იიიიიიი	UNUUUULU	רמחמרחרר	าลสภากาก	חמר מתח	กกวากกก	229.00	190051	179.00
1,9800	บบเมษยนานบนตามนานบนบนนานบนบนบนบนบนบนบนบนบนบนนานบนบนบนเหมษยนหมา 229,19 163,54 123,09	ากกาวกา	<b>UUUUUKUUU</b>	กอกกกกก	กบรบบรบบร	טטטיאטטט	กลกกกกก	229.10	163,54	123,00

23 THE NUMBER OF ITERATIONS MAS

Piston Temperature Profiles Table 7 (continued)

CERAMIC = 40/1600, POWER= 50 PER CENT

00.0	0.11	0.25	0.38	0.00 0.11 0.25 0.38 0.57 0.75 1.00 1.25 1.50	0.75	00.1	1.25	1.50	1.60
1 1 5	e C	511.00	515.00	519.00 511.30 511.00 515.00 519.00 576.00 514.00 518.30 553.00 503.00	526.00	514.00	518.30	553,00	503,00
•	0	00.00 00.00 00.00	00.0	00.0 00.0 00.0	00.0	00.0	00.0 00.0		0.00 215.00
0.0	_	00.0 00.0 00.0	00.00	0.00	00.00 00.00	00.0	00.00	00.00	0.00 203.00
225•00		229.00	228.00	230.00 225.00 229.00 228.00 228.00 229.00 229.00 209.00	229.00	229.00	209-00	0.00	00 00 100 00
ררנטטטי		กกกากกกก	กกกากกก	กยนายนายนายนายนายนายนายนายนายนายนายนายนาย	מטטריטטט	กกกากกก	1 99 •00	06*0	0.00 165.00
מרנממתו		กลกภภภภภ	ລກກກກກກກ	กษณะบนแบบมากระบายการแบบมาการแบบมาการแบบมาการแบบมาการแบบมาการแบบมาการแบบมาการเกาะ	กกกรากกก	กลภากกา	199.00	00.00	0.00 118.00

THE TOTAL FEAT FLOW RATE IS 1765-41900BTUZHR

DISTANCE	00 0	9.11	0.25	0.38	0.50	0.75	1 • 00	1.25 1.50	1.50	1.60
0 0 0 0 0 0	510.00	511.00	£11.00	515.00	510.00 511.00 511.00 515.00 519.00 506.00 514.00 518.00 503.00 503.00	506.00	514.00	218.00	503.00	503.00
00.0.0	257.09	257.08	256.93	256.85	257.09 257.09 256.93 256.85 256.82 255.14 251.86 238.87 224.94 215.00	255014	251.86	238.87	224.94	215,00
Cr 2300	24 2. 56	242.47	242.30	241.99	242.56 242.47 242.30 241.99 241.74 240.70 236.76 222.79 2C8.93 203.00	240.70	236.76	222,79	208.93	203.00
0.4100	230.00	555.00	229.00	228.00	230.00 225.00 229.00 228.00 228.00 229.00 225.00 219.00 195.77 190.33	229.00	225.00	239.00	195.77	00*061
C. 2563	UNIQUEBUMUDELLUGULUSKUNDUNLULNISSUNISSUNISSUNISSUNISSUNISSUNISSU	חחרוחחחר	USCUCUU	LUCCOUVI	UUTUULTUU	വസസസ്യ	იიიიიიი	159.00	172.27	165.00
1.0 100	UNUTURUULELLETULUUVULLUULUULLUULUUUVUULUUUUUUUUUU	רמרנמחנ	מממתנינים	וחחרתחת	<b>UUUUUUUU</b>	იიიიიიი	กกากกก	199.10	149.92	118.00

THE MINBER OF ITERATIONS HAS 20

Table 7 (continued) Piston Temperature Profiles

CERAMIC = 40/1000, FIMER 25 PEP CENT

DISTANCE	3.00	11.6	3.25	0.38	3.53	0.75	3.00 3.11 3.25 0.38 3.50 9.75 1.00 1.25 1.50 1.60	1.25	1.50	1.60
0000-0	561.00	546.30	530.00	508.00	435.00	492.30	561.00 546.00 530.00 508.00 435.00 492.00 494.00 454.00 491.00 491.00	4 54 •00	491.00	491.90
00+0+0	00*0	00.5	00.00 00.00 00.00	00.0	00.0	00 •0	0000 0000 0000	00.00	0.00 0.00 192.00	192.00
0° 5300	0.00	00.00 0.30 00.00	0.00	00 • 0	0.00	00-0	0000	00•0		0.00 184.00
0.4100	204.00	203.00	202.00	201.00	292.00	203,00	204.00 203.00 202.00 201.00 202.00 203.00 203.00 183.00	183.00	<b>6</b>	0.00 175.00
0, 856.0	กษณ์ของของการแบบการแบบการแบบการแบบการแบบการแบบการแบบการแบบการแบบการแบบการแบบการแบบการแบบการแบบการแบบการแบบการ	าดคลา <b>าลด</b>	กกกกกกกก	กกกกกกกา	บบบบบบบบ	UNICOLOGIC	nnnnnn	173.00		0.00 158.00
1.0800	อนมีขอยอยยยยยยยยยยยยยยยยยยยยยยยยยยยยยยยยยย	ררניחתחת	กกกกกกก	กากกากกา	חרחחחחח	<b>ก</b> กกกกกกก	UUUUUUU	173.00		0.00 118.00

THE TOTAL PEAT FLOW RATE 15 1780.

1780.29100ETU/HR

DISTANCE	00.0	0.1	7.25	0.38	7.25 0.38 0.50	0.75		1.25	1.00 1.25 1.50	1.60
0000	561.00	546.00	530.60	508-00	546.33 530.07 508.03 435.00 492.09 494.00 494.00 491.00 491.00	492.09	494.00	494.00	491.00	491.00
0.0400	236.91	235, 77	234.17	232.21	236-91 235-77 234-17 232-21 230-53 230-33 226-98 214-89 205-81 192-00	230.33	226.9B	214.89	205.81	192,00
0.2300	219.21	217,92	217.13	216.33	219.21 217.92 217.13 216.33 215.8E 215.27 211.61 158.82 189.39 184.00	215,27	211.61	158.82	189,39	184.00
6,4100	204.00	293.09	2 72 • 00	291.90	204.00 203.00 272.00 201.00 202.00 203.00 203.00 183.00 178.00 175.00	203.00	203.00	183.00	178.00	175.00
0.8 60	VOUCHURANDE CONTROLLE CONT	กกกากกก	UU UU UU UU	ומרמרמני	ממממתחרה	กกกกกกกก	กกกกกกก	173.00	160.35	158.00
1.7800	ՍԱԼԿՍՍՍԱՄԵՍԵՍԱՍՍԵՐԽԱՍՎԿԱՍ ԷՍՍՍԵՍԱՍԱՍԱՄԱՄԱՍԱՍԱՍԱՍԱՍԱԱՄԱ 173.00 141.44 1118.00	າດກາດາດາ	เมนบบเนย	เขบบบบบ	กากกกกกก	าบบบบบบบ	ດດາດດາດ	173.09	141.44	118.00

THE MUMEER OF ITERATIONS NAS 19

CERAMIC = 40/1/09, SOMER= 1 PER CENT

DISTANCE	00.0	0.11	0 - 25	0.38	1.50	9.75	0.00 0.11 0.25 0.38 7.50 0.75 1.00 1.25 1.50 1.60	1.25	1.50	1.60
000000	498.00	461.99	423.00	445.00	475.00	473.00	498.00 461.00 423.00 445.00 475.00 473.00 480.00 485.00 434.00 484.00	485.60	4 3 4. 0 0	484.00
2,7430	00 •0	00.00	00.0	00.0	00.0	00.00	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	00.0	00.00	159.00
0.2301	00.0	0.00 0.00 0.00 0.00 0.00	0.00	00.0	0.00	00.00	0000	00.00		0.00 154.00
d. 4100	163.00	162.00	162.90	162.00	163.00	164.00	163.00 162.00 162.00 162.00 163.00 164.00 165.00 145.00	145.09	00.00	0.00 148.00
0.8560	ลดากกลาย เราะบบ เป็นเป็น เป็น เป็น เป็น เป็น เป็น เป็น	מרור המחר	กกกกกกกา	רטטטטטט	กากกกกกก	บบบาบบบ	ດດກາດດດ	135.20	00.0	0.00 137.00
1,0800	60*561 กลากกลากกลากกลากกลากกลากกลากกลากกลากกลา	າກດດວ <b>ດກ</b> າ	ກດກາກກາກ	กลกกกกก	ກກດດດ <b>ກ</b> າກ	ດດດດດດດດດ	מחמתרמה	00*981		0.00 1111.00

1869.32100BTU/HR
S
RATE
FL 04
1421
INTAL.
1 1 1 1

DISTANCE	00 • 0		9.25	6, 73	0-11 0-25 0.73 7-59 0-75 1-00 1-25 1-50 1-60	0.75	1.00	1.25	1.50	1.60
000000	498.00	461.00	423.00	00.5.4	498.00 4£1.00 423.00 A45.00 475.00 473.00 A80.00 485.00 434.00 484.00	473.00	480.00	485.04	434.00	484.00
0.040.0	194.23	191.95	189.75	191.69	194.23 191.95 189.75 191.69 153.75 192.74 191.76 181.43 176.55 159.00	193074	191.76	161.43	176,55	155.00
C+ 2300	176.71	176.46	176.33	176.87	176.71 176.46 176.33 176.87 177.60 177.66 175.16 163.95 158.85 154.00	177.66	175.16	163,95	158,85	154.00
0.4100	163.00	162.00	162.00	162.00	163.00 162.00 162.00 162.00 133.00 164.00 165.03 145.00 148.34 148.00	164.00	165.03	145.00	148,34	148.00
C. £562	บนบบตนนนนนนนายบนเทยบนเทยบนนน นบนนนนนนนเทยบนเทยบนเทยบายเกราหาย 135,00 135,54 137,00	มองเยอยย	บบบบบบบบ	เบนนนนนา	บบบบบบบบบ	เกษาเกษา	DODO DO D	135.00	135.54	137.00
1.0800	ՄԱՄԱՄԱՄԱՄԵՐ ԷՄՄԱՆ ՄԱՄԱՆ ՄԱՄԱՄԱՄԱՄԱՄԱՄԱՄԱՄԱՄԱՄԱՄԱՄԱՄԱՄ	חברנתמתרו	<b>1000 (MO</b> 0	กลกลากกา	מתמתחתרי	กกกกกกกก	იიიიიიი	135,30	123,18	111.00

THE NUMBER OF ITERATIONS MAS 19

Table 7 (continued)
Piston Temperature Profiles

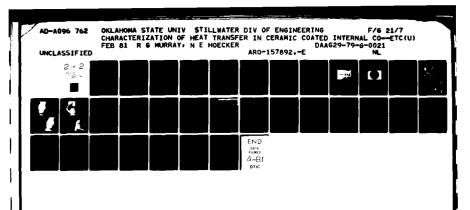
CERAMIC = 30/1001, P34EP= 100 PER CENT

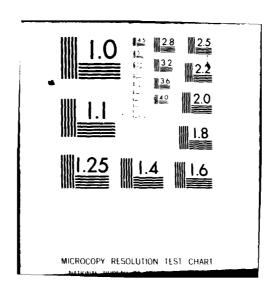
1.60	560.00	281.00	265.00	250.00	0.00 218.00	142.00
1.50	560.00	0000	0.00	00.0	00 00	00.0
1.25	556.00 562.00	00 • 0	0000	289.00	279.00	279.00
1.00	556.00	0 • 0	00.0	309-00	กกกกกกก	ດດາດດດາ
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7.53	523.00	00.0	00.0	307.00	იიიიიიი	กากกกกกก
0.38	520.00 515.00 510.00 517.00 523.00	00.0	0.00	309.00 307.00 306.00 307.00 308.00	רטטטטייטט	המורוה
7.25	510.00	00 • 0	00.0	307.00	ยดของจาย	ירמתחרחתה
3.11	515.00	00.0	0.000		מחררממחר	ורררהחחר
00°0	520.00	00 • 0	00°0	309.00	บบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบ	ก <b>บานบานบานบานบานบานบานบานบานบานบานบานบานบ</b>
DISTANCE	000000	000000	0061 %	0.3700	0.8160	1.0500

THE TOTAL PEAT FLOW RATE IS 16203.26000ETUZER

DISTANCE	00.0	1110	0.25	0.38	0.00 0.11 0.25 0.38 0.50 0.75 1.00 1.25	9• 75	1.00	1.25	1.50	1.63
00000	523.00	515.00	510.00	517.00	523.00 515.03 510.00 517.00 523.30 523.00 556.00 562.00 560.00 560.00	523,00	556.00	562.00	560,00	560.00
000000	520.00	515.00	210.00	517.00	520.00 5:5.00 510.00 517.00 523.00 523.00 556.00 562.00 560.00 281.00	523.00	556.00	562.00	560.00	281.00
0061-0	40.8-91	436.47	438.17	409.E4	473.91 43f.47 438.17 409.E4 411.58 414.56 422.60 467.53 347.61 265.00	414.56	422.60	467.53	347.61	265.00
Co 3700	30 3, 00	3 C H+ 00	337.03	306.00	303,00 368,00 307,00 306,00 307,09 308,00 309,00 289,00 272,61 250,00	308.00	309.00	289.00	272.61	250.00
0.4169	องเหติงของของ เล่าเกลายายของเล่ามีของของจาก เล่ามีของของ เล่ามีของของ เล่ามีระดัง	בהו במתמב	บบบบบบบบ	רמממרמרמ	กบบบบบบ	מתחתר מתחו	מממרנימים	279.00	231.67	218.00
1-0500	บบบบ ซนา ซนา ซนา เมษา มหาย มหาย มหาย มหาย มหาย มหาย มหาย มหา	מניטטט נטס	טע אנייטטטט	ונו זממניגניז	บบบบบบบบ	וטטגייישטטנ	ດດດດດດດ	279.00	154.29	142,00

THE NUMBER OF ITERATIONS WAS 21





CERAMIC # 00/1000, POWER# 75 PER CENT

DISTANCE	00.0	0.00	9 - 25	0.38	0.25 0.38 0.50 0.75 1.00 1.25	0.75	1 •00	1.25	1.50	1.60
0.0000	521.00	521.09 527.09 532.00	532.00	536.00	536.00 540.00 555.00 550.00 539.00 537.00	555,00	550.00	539.00	537.90	537.00
6.0000	00 00	00 00	00.00 00.00		00.0 00.0 00.0 00.0	0.00	0 0 0	00.0	0.00	250.00
0.1900	0.00	0.00	0.00	0.00	00.00	9,00	0000	0.00	00.00	239.00
Ge 3700	27 6. 00	275.00	274.00	272.00	276.00 275.00 274.00 272.00 273.00 275.00 274.00 254.00	275.00	274.00	254.00	0000	227.00
09 19 00	บนของชาบนยะเ.เยยยนชยยยยยยยยยยยยยยยยยยยยยยยยยยยยยยยย	מרונחחחה	იიიიიიიი	LULUUUUU	กกกกกกกก	กากกากกา	ממחחחח	244.00	0.00	204.00
1.0500	บบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบบ	กกรากก	OCCUPATION OCCUPATION	ທາດທາດກາ	ທາດນານນາ	างของของ	ODDOOD	244.00	800	0.00 130.00

THE TOTAL PEAT PLOW RATE IS 17780.42000BTU/HR

DISTANCE	0.00	0.00 0.11	0.25	0.36	0.50	0.75	0.50 0.75 1.00	1.25	1.50	1.60
0.0000	521.00	527.00	532.00	536.00	527.00 532.00 536.00 mm.np	555.00	550,00 539,00 537,00	539.00	537.00	537.00
0.000	521.00	527.00	532.00	536.00	527.00 532.00 536.00 E40.00 ESE.00 550.00 539.00 537.00 250.00	555,00	550.00	539.00	537,00	250.00
0-1960	398-54	359-16	400-41	+01-14	398-54 359-16 400-41 401-74 433-72 408-37 402-77 380-54 322-14	408.37	402.77	380.54	322.14	239.00
0012.0	276.00	275.00	274.09	272.00	275.00 274.09 272.00 273.00 275.00 274.00 254.00 246.99 227.00	275-00	274.00	254.00	246.99	227.00
C. 91 60	UULUI URUUUREELUUULUUULUUULUUULUUUUUUUUUUUUUU	ากกกากกก	UUUUUUUU	กกากกกกา	กากกกกกา	JUUUUUU	nnnnnn	244.00	211.87	204.00
1.0500	UNUVUUUUULLIUUULLUUULUUULUULUULUULUUUUUUUU	חהרוחחחר	กกากกกกา	าากกากกา	กาดกดกกด	ໝານນານ	ממטחממ	244.00	175.71	130.00

THE MUMBER OF ITERATIONS LAS

Table 7 (continued)
Piston Temperature Profiles

CEGAMIC = 00/1000, POWER = 50 PER CENT

DISTANCE	0.00	0.00 0.11 0.25	<b>3.25</b>	0.38	3.50	9.75	1 • 00	1.25	1.50	1.60
0-00-0	260-00	560.00 559.00 558.00 562.00 566.00 555.00 564.00 537.00 535.00	558.00	562.00	566.00	558.00	564.00	537.00	535.00	535.00
0000.0	00.0	0.00	0.00	00.00		0. 00	00.00 00.00	00°C	0000	235.00
0961 0	00 0	00 00	00.0	0.00	00.0	00.0 00.0	0	0	0000	227.00
0.3700	24 3.00	243.00 242.00 241.00 240.00 240.00 241.00 242.00	241.00	240.00	240.00	241.00	242.00	222.00	0.0	218.00
0. 8160	บยนมนะบนนนนะ เลยายนนมนะ เลยายน	מחררמממת	ພວນພວນ	กกกกกกก	กลดดดกกก	<b>ບບບບບບບ</b>	OCCOUNT	212.00	0000	201-00
1.0500	WWW.VVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVV	10001100	WWWWW	וממממחרמ	ລຄດກາກກາດ	Mananan	OCOUNT	212 000	0.0	123.00

19763.42000ETU/FR THE TOTAL PEAT FLOW RATE IS

**VOLUMENTAL VERY VALVA VA** 365,33 222.00 537.00 537 .00 1.25 391-26 241.00 240.00 240.00 241.00 242.00 564.00 564.00 ..8 397.02 393.72 555.99 555.00 0.75 266.00 266.00 0.50 356.63 562.00 562.00 0.39 396.14 396.04 558.00 558.00 0.25 243,00 242,00 559.00 655.00 0.11 396.27 360.00 560.00 00° c DISTANCE

0.000.0 0.000.0 C. 3700 0.8160 1. : 509

0.1900

218.00

227.00 235.00

311.19 232,86

535,00 535.10

1.50

123.00

2 THE NUMBER OF ITERATIONS HAS

Piston Temperature Profiles Table 7 (continued)

CERANIC # 00/1000, POWER# 25 PER CENT

DISTANCE	00.0	0.11	0.25	6 a G	0.00 0.11 0.25 0.36 0.50 0.75 1.00 1.25	<b>0.</b> 75	9	1.25	1.50	09•1
G- 3309	51 7. 00	535,00	552.00	560.00	517.00 535.00 552.00 560.00 568.00 560.09 558.00 561.00 555.00	569,09	558.00	561.00	555.00	559.00
0.000.	00 •0	0.00	0.00	0.0	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 210.00	0.00	0.00	0.00	00.0	210.00
0.1900	00.0	00.00	0	00.00 00.00 00.00	0.00	0.00 0.00	0000	00.00		0.00 201.00
6, 3766	21 5. 00	214.00	214.00	213.00	215.00 214.00 214.00 213.00 214.00 215.00 215.00 195.00	215.00	215.00	195.00	0.0	0.00 192.00
0916.0	กษณะบบบานของเกลย และเล่า เกลย และเล่า เกลย เกลย เกลย เกลย เกลย เกลย เกลย เกลย	กกกกกกกก	WUUU UUUU	וחחחחחח	วาดกกกกก	חחחברחחח	COULOU	185.00	0.00	0.00 173.00
1.0500	บนเมนนนนนนนนนนายายายายายายายายายายายายายายา	wurwu	ພວນອອ	LUUUUUUU	ກາດໝາດກາ	ON ON ON ON ON	DUDDUD	165.00		0.00 121.00

THE TOTAL PEAT PLOW RATE IS 22136,69000ETU/HR

DISTANCE	00.0	11.0	9.25	0.38	0-11 9-25 0-36 0-50	0.75	00-75 1-00	1.25	S	8
0.000	917.90	535.00	552.00	560.00	83€.00 552.00 560.00 B68.00 560.00 558.00 561.00	560.00	\$58.00	561.00		559-00
0.0000	517.09	535.00	552.00	560.00	\$35.00 552.00 560.00 568.00 567.03 558.00 561.00 555.00 210.00	569.09	556.00	561.00	555.00	210-00
0.1900	37 3. 20	376.21	379.27	382.01	373.20 316.21 379.27 382.01 364.14 381.90 377.38 359.27 258.69	381.90	377.38	359.27	258.69	201.00
0-3700	21 5.00	214.00	214.00	213.00	215.00 214.30 214.00 213.00 214.00 215.00 215.00 155.00 236.87 192.00	215.00	216.00	155.00	208.87	192.00
0.6169	WWW.UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU	חרררתחחר	กากกากกาก	กกลดดกกา	ກາດກາກກາກ	CONTRACTOR	WUWW	165.00	174.95	173.00
1.0500	WWW.WWW.WWW.WWW.WWW.WWW.WWW.WWW.WWW.WW	ກດດເຂດດດ	<b>WWWWWWWWWWWWWWWWWWWWWWWWWWWWWWWWWWWWW</b>	רטעעעעעע	กกลากกาก	กากกากก	CONTOCOL	185.00	149.08	121-00

THE MUREER CF ITERATIONS 1AS 21

Table 7 (continued)
Piston Temperature Profiles

SISTANCE	02.0		3.25	0.00 0.00 0.00	1511 1625 0638 1651 0675	0.75		1.00 1.25 1.50	1.50	1.60
00.00	507.00	516.09	525.00	523.00	507.00 516.00 525.00 523.00 520.00 520.00 515.00 517.00	520.00	515.00	00*215	515.00 515.00	515.00
30(548	9.00	9,00	9-59 0-03	0000	0000	00.00	00.0	0.00	0.00	0.00 169.00
0001.0	0.00	6. 00	00.00 00.00	00*0	00.0	0.00	0000	0.00	00.0	0.00 163.00
0-3100	177.00	176.30	176.00	175.00	177.00 175.10 176.00 175.00 176.00 177.00 177.00 157.00	177.00	177.00	157.00	0000	0.00 158.00
9, 8160	บนตับของอยายยายยายยามายยายยายยายยายยายยายยายยายยา	าผลภากกา	กกากกกกก	เบบบบบบบ	ດກາກດາກຄ	טטטיטטטטט	ດດກາກກາ	147.00	0000	0.00 146.00
1.0500	00*2*1 การการการการการการการการการการการการการก	חחרוהחחר	<b>ດດດກດດດດ</b> ດ	าากกกกกา	กากกกกาก	ภากกกกก	nmnnnn	147.00	00.00	0.00 115.00

THE TOTAL PEAT FLOW RATE IS 21862.840608TU/HR

DISTANCE	00.0		<b>3.</b> 25	0.38	0+11 0+25 0+38 0+50	0.75		1.00 1.25	1.50	1.60
0° 00 ° 0	597.00	516.00	525.00	523.00	597.00 516.09 525.00 523.00 520.09 529.09 515.00 517.00 515.00	529.09	51 5.00	217.00	515.00	515.00
9.00.0	507.00	516.00	525.09	523.00	507.00 516.00 525.09 523.00 529.00 520.00 515.00 517.00 515.00 169.00	520.00	215.00	517.00	515-00	169.00
3,1903	342.16	343.00	344.33	343.94	342.16 343.00 344.33 343.94 343.37 342.67 336.43 319.05 259.72 163.00	342.67	336.43	319.05	259, 72	163.00
7,3700	177.00	176.00	176.00	175.00	177.00 176.00 176.00 175.00 176.00 177.00 177.00 157.00 173.59 158.00	177.00	177.00	157.00	173,59	158.00
0.9160	UNUNUNUNULLUUUULUUUUUUUUUUUUUUUUUUUUUU	חהררחחחת	טטטטטטטט	ເບບບບບບບ	טרטטטרט	າດດດດດດດາ	ממתרמממ	147.00	146.07	146.00
1, 9599	บษษายนยนยน เป็นการของเกษายน เป็น เป็น เป็น เป็น เป็น เป็น เป็น เป็	חררמתמחת	กกกกกกกก	<b>LUUUUUUU</b>	שטיאטניטנ	יטטטטטטטט	DONO DO	1.7.00	130,28	115.00

THE NUMBER OF ITERATIONS WAS 21 Statements executed = 158470

3		32 V 2LO
		WATFIV - MAR 1983 V2LO
BYTES	0	WATELV .
2464 BYTES, TOTAL AREA AVAILABLE 133120 BYTES	0. NUMBER OF EXTENSIONS=	8 JAN 91
TOTAL AREA AN	0. NUMBER	THURSDAY
2464 BYTES.	# ARN INGS#	21.15.09
8248 EVTES,AGRAY AREA	0. NUMBER CF # ARNINGS=	3.45 SEC.
48 EYTE	H	N TIME
fBJECT CODE≈ 82	NUMBER OF ERFORSE	A.15 SEC.EXECUTION TIME
CORT USAGE	DIAGNISTICE	COMPILE TIMES

Piston Temperature Profiles

Table 7 (continued) -

0.10000 NOTE THE UPPER LEFT HAND CORNER IS THE TOP CENTER OF THE PISTON OR VALVE. THE TOLEFANCE FOR CHANGE IN AVG ELEWENT TEMP BETWEEN ITERATIONS IS 0.10000 THE THEF MAL CONDUCTIVITY FOR THE INSULATION IS 0.40000 THE TOLEFANCE FOR MAXIMUM CHANGE IN TEMPERATURE IS THE THERMAL CONDUCTIVITY FOR THE METAL IS 33.00000

Table 8

INFRARED TO THERMOCOUPLE HEAT FLOW

CERAMIC	PERCENT	HEAT FLOW BTU/HR	
THICKNESS INCHES	POWER	PISTON	VALVE
.10	100	736	35
.07	100	888	61
. 04	100	1321	131
.00	100	16203	3197
.10	75	706	27
.07	75	980	153
.04	75	1619	233
.00	75	17780	3118
.10	50	703	78
.07	50	1082	158
.04	50	1769	120
.00	50	19763	3203
.10	25	740	111
.07	25	1284	133
. 04	25	1780	220
.00	25	22137	449
.10	MIN	789	116
.07	MIN	1399	160
.04	MIN	1869	199
.00	MIN	21863	1579

Table 9
THERMOCOUPLE TO THERMOCOUPLE HEAT FLOW

CERAMIC THICKNESS INCHES	PERCENT POWER	PISTON HEAT FLOW BTU PER HOUR
.10	100	2311.
.07	100	2180.
.04	100	2844.
.00	100	2806.
.10	75	1951.
.07	75	2128.
.04	75	2592.
.00	75	2813.
.10	50	2352.
. 07	50	1832.
. 04	50	2186.
.00	50	3646.
.10	25	1632.
.07	25	1502.
.04	25	1936.
.00	25	2696.
.10	MIN	935.
.07	MIN	1159.
.04	MIN	1254.
.00	MIN	1521.

durance test performed under an earlier grant.

The purpose of this test was to identify failure modes of zirconium oxide coatings in internal combustion engine combustion chambers. Three types of metal are commonly found in engines: aluminum, cast iron and steel. It was, therefore, desirable to test the behavior of all three materials with various coating thicknesses.

To satisfy the test criteria, a 1952 Chevrolet 216 cubic inch, 6 cylinder engine was selected. This particular engine was chosen since both cast iron and aluminum pistons are available. This engine was remanufactured and fitted with new oversize pistons, three, of which were cast iron and three were aluminum. Prior to assembly, the pistons were coated with a nominal 0.03, 0.06 and 0.10 inch coating of yttrium stabilized zirconium oxide. The piston tops were machined to reduce thicknesses so that all pistons would have the same height after coating. The valves and combustion chamber walls were also coated with ceramic to the above thicknesses. Figures 29 and 30 portray typical preassembly component details.

The engine was assembled and operated on a simulated driving cycle for a first 1000 hours. This driving cycle consisted of 23 hours plus 55 minutes at 2000 rpm at 30% of maximum power, followed by 5 minutes at full power also at 2000 rpm. No operational data, except time, was recorded.

Following the first 1000 hours, the engine was disassembled and inspected. No significant coating degradation was found, except on the perimeter of the intake valves; here, most of the ceramic had separated.

The second 1000 hours test proceeded after an engine overhaul that included new piston rings and bearings.

The second test was conducted with the same simulated driving cycle. Forty hours into the second 1000 hour test, a generator failure resulted in the fan belt failure. This, in turn, caused high engine temperature. A coincidental failure of the safety switch allowed the engine to run to seizure. Following this problem, the engine was again overhauled and placed into service with all of the original ceram-

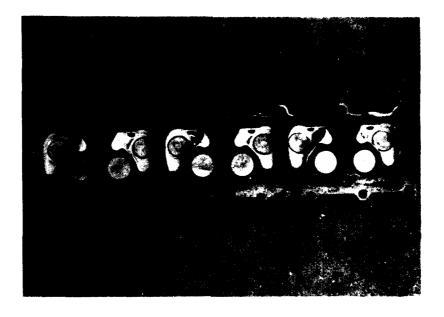


Figure 29: Endurance Engine Cylinder Head

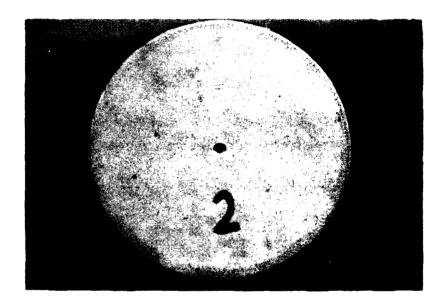


Figure 30: Endurance Engine Piston

ic surfaces.

After 2000 hours of exposure, the engine was disassembled and inspected. As before, no significant problems were observed with the coating. The piston surfaces had some heat cracks and some feathering on the perimeter; no additional separations had occurred, however, since the first 1000 hours.

Figures 31-36 portray typical surfaces after 2000 hours of operation. Note that some surfaces seem abraded and, in some cases, this condition goes to the base metal. This abrasion is the result of glass bead blasting that not only removed carbon deposits, but also, the ceramic coating. The coating was secure and in place prior to blasting.

### SUMMARY AND CONCLUSIONS

The preceding document outlines details of a study of heat transfer, temperature profiles and endurance for ceramic coated internal combustion engine parts. Such parts offer significant promise in the advancement of engine technology.

The first objective of the study was to create a mathematical model that could predict heat transfer and temperatures within coated pistons and valves. This model was developed, and is presented, in computer card format. With this model, a design engineer should be able to optimize such parts for any engine application.

The second objective was to measure operational temperatures of a piston and a valve with various thicknesses of coating at various power levels. To do this, two rather novel techniques were used. Thermocouples were installed in moving crankcase piston surfaces and the signal was routed by hard wire techniques out of the crankcase. This procedure was quite successful and produced excellent results.

The second technique incorporated fiber optic probes to measure combustion chamber surface temperatures using infrared detectors. This procedure produced poor results in spite of extensive calibration efforts. It is believed that this method can be made to work, and with additional development will be an extremely valuable tool for

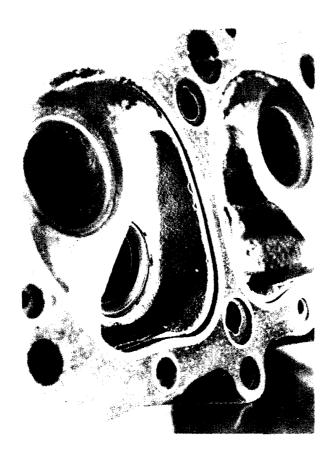


Figure 31:

Cylinder Head Surfaces

Figure 32:

Cylinder Head Surfaces

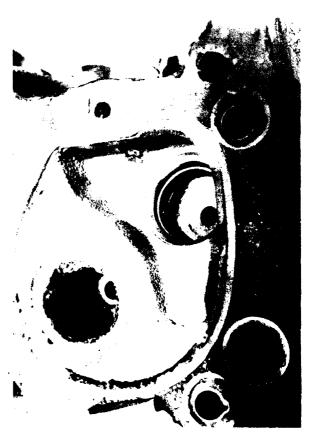
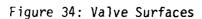




Figure 33: Valve Surfaces





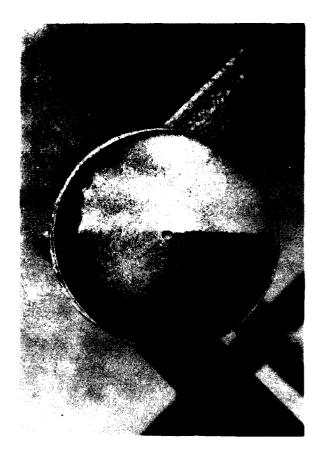
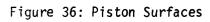
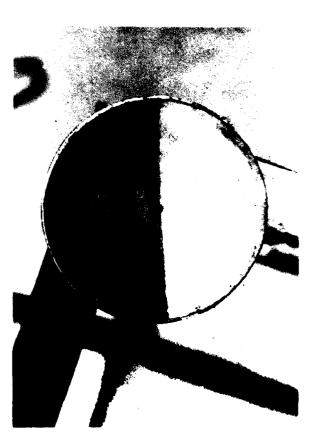


Figure 35: Piston Surfaces





engine research.

It is recommended that additional efforts be undertaken to perfect the fiber optics, infrared technique.

The third objective was the continuation of an earlier 1000 hour endurance test of ceramic coated engine parts. This final test added a second 1000 hour of time to the existing engine. This effort proved without doubt that ceramic coated parts can endure the torturous environment of I-C engines without significant degradation.

### **ACKNOWLEDGEMENT**

The authors wish to express their appreciation to the U.S. Army research office for the opportunity to examine this most important area of engine technology.

They also wish to express their gratitude to the dedicated staff that made the project a success.

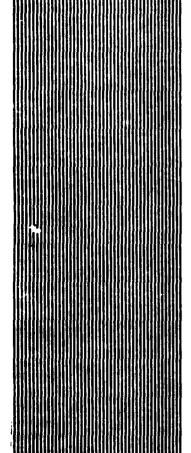
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Appendix 1



### THERMOPHYSICAL PROPERTIES RESEARCH LABORATORY



**TPRL 194** 

Thermophysical Properties of a Coating

A Report to Oklahoma State University

by

R.E. Taylor and H. Groot

August, 1979

School of Mechanical Engineering
Purdue University, West Lafayette, Indiana

### **TPRL 194**

Thermophysical Properties of a Coating

A Report to Oklahoma State University

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### Thermophysical Properties of a Coating

### **INTRODUCTION**

Four duplicate samples of a zirconia coating on a steel sample were furnished by Dr. Murray of Oklahoma State University for thermal conductivity determinations. The samples were nominally 0.5 inch diameter and 0.1 inch thick with the steel comprising a little over one-half of the thickness. The basic approach to be used to determine the thermal conductivity "k" was to measure the thermal diffusivity, "a", specific heat "C " and density "d" since  $k = \alpha C_p d$ . The bulk densities were determined from mass and geometry measurements, the specific heat was measured using a differential scanning calorimeter, and the thermal diffusivity "a" was measured using the laser flash method. This technique for obtaining thermal conductivity is widely used and has the advantages of simple small sample size, and the climation of the heat flux and temperature gradient measurements. These later measurements, combined with extraneous heat flows, are the primary resons why direct conductivity measurements are difficult and often yield poor results.

The Perkin-Elmer DSC II differential scanning calorimeter is used for routine determinations of specific heat up to 700° C. The differential heat required to heat the sample and a standard saphire specimen is measured. From the mass of the sample and the saphire and the known specific heat of saphire, the specific heat of the unknown can be calculated. A continuous recording of microcalories versus temperature is obtained during the experiment.

The flash method in which the front face of a small disc-shaped sample is subjected to a short laser burst and the resulting rear face temperature rise is recorded, is used in over 80% of the present thermal diffusivity measure-ments throughout the world. A highly developed apparatus exists at TPRL and we have been involved in an extensive program to evaluate the technique and broaden its uses. The apparatus consists of a Korad K2 laser, a high vacuum system including a bell jar with windows for viewing the sample, a tantalum tube heater surrounding a sample holding assembly, a spring-loaded thermocouple, appropriate biasing circuits, amplifers, A-D converters, crystal clocks, and a minicomputer-based digital data acquisition system capable of accurately taking data in the 40 microsecond and longer time domain. The computer controls the experiment, collects the data, calculates the results, and compared the raw data with the theoretical model. A typical visual display

is shown in Figure 1. The raw data are given in Table 1 and the computations are given in Table 2. The vertical axis of Figure 1 is non-dimensional temperature rise (the temperature rise at anytime divided by the maximum rise). The horizontal axis is non-dimensional time (the time from the initiation of the laser pulse divided by the time to reach one-half of the maximum temperature rise). The solid curve represents the theoretical model and the points are the actual data. Note the close agreement between the experimental data and the mathematical model (Figure 1). The calculated results given in Table 2 were obtained from the computer output of Table 1. The column headed "ALPHA" are the diffusivity values (cm<sup>2</sup> sec<sup>-1</sup>) calculated assuming no finite pulse effect at various percent rises (PER). The column marked "VALUE" is the emf output corresponding to the percent rise and "TIME" represents the time in seconds from the initiation of the pulse until the rear face temperature rise reached the indicated percent value. The resulting values of  $\alpha$  range from 0.00309 to 0.00321 between 10 and 80% of the temperature rise (Table 2) and the best value is 0.00320 cm<sup>2</sup> sec<sup>-1</sup>.

A special technique has been developed to measure the thermal diffusivity of one layer in intimate contact with a second layer. The half-time for the composite is measured and the rise curve is compared to the theoretical model in the usual fashion. In order to use this method, it is necessary to know the thicknesses, specific heats and densities of the two layers and the diffusivity of the second layer. Thus these properties were measured for the steel sample using a blank furnished by Dr. Murray. However, the rise curves for the composite samples did not follow the theoretical model, showing that interfacial contact resistance was present. A typical result is shown in Figure 2. Note the differences between the theoretical and experimental rise curves. Since the coatings were reasonably thick and could be removed from the substrate, the diffusivity of the free-standing coating was measured directly. In fact the visual display of Figure 1 and the data of Tables 1 and 2 are from the free-standing coating at room temperature.

### RESULTS

The thermal diffusivity results for the coating and for the steel blank are given in Table 3. The diffusivity results for the coating are plotted in Figure 3. It was noted that the diffusivity values were unstable with time between 250 and 500° C and consequently measurements were made during the cooling cycle. These values were significantly less than those attained during initial heating.

The specific heat results for the coating and for the steel are given in Table 4 and plotted in Figure 4. A large peak was noted in the specific heat of the coating during the initial heating cycle (Figure 4). Thus the sample was rerun and the peak disappeared. This behavior occured over the same temperature range in which the diffusivity values were unstable (Figure 3) and the two phenomena are undoubtedly related.

Thermal conductivity values are calculated in Table 5 and plotted in Figure 5. No calculations were made between 300 and  $500^{\circ}$  C for the initial heating data as the specific heat and diffusivity values are certainly time-temperature dependent. However the cooling curve data (diffusivity) and second run data (specific heat) are representative of this material after temperature cycling to  $500^{\circ}$  C ( $1000^{\circ}$  F).

With the knowledge of the thermal properties of both layers, it is possible to calculate the contact conductance for the two-layer case. These values ranged from 2.4 to 4.2 W cm<sup>-2</sup> K<sup>-1</sup> at room temperature for the three samples which were not sectioned.

The conductance values at higher temperatures or the changes caused by temperature cycling were not determined, although it would be possible to do so.

### DISCUSSION

The changes in specific heat and thermal diffusivity (and consequently conductivity) noted during initial heating are undoubtedly due to the removal of a contaminant. We have often observed similar phenomena on other samples of materials which were significantly less than theoretical density. The sensitivity and accuracy of advanced computer-aided instrumentation and methods makes such changes readily discernable. However, unless one is interested in initial heating conditions, one should use the values generated during the cooling or second run curves.

### TABLE 1

### Experimental Data

### OKLA. STATE UNIV. COATING AIR 23C

RUN # 1 ON 7/29/71; SAMPLE THICKNESS: 0.1046 CM;

DURATION: 2.200000 SEC.; 0.10000 SEC. BETWEEN TRAILING READINGS;

SHORT BASELINE;

NO WILDNESS & SMOOTHING PERFORMED;

VOLTAGE	TIME		
0. 47363159	Ο.		
0. 50048 <b>699</b>	44300.		
0. 5126940 <b>0</b>	99610.		
0. 5590304 <b>0</b>	154920.		
0.86181420	210230.	INITIAL VOLTS	FINAL VOLTS
1, 27196937	2655 <b>30</b> .	0. 48827999	
1.71530419	3208 <b>30</b> .	0. 48339720	5. 31004503
2, 20214277	37615 <b>0</b> .	0. 51269400	5. 3465659 <b>7</b>
2. 63915337	431460.	0. 55175639	5. 33690042 5. 37596277
2. 95453 <b>534</b>	486760.	0. 48827999	_ · ·
3, 29539001	542050.	0. 50781119	5. 44920481
3. 50838919	597370.		5. 40525957
3.811025 <b>39</b>	65268 <b>0</b> .	0. 47363159	5. 41502520
4.00977878	7080 <b>00</b> .	0. 43827999	5. 39549395
4. 19676661	753300.	0. 54199080	5. 45408762
4. 37254734	818600.	0. 52245959	5. 44920481
4, 44923078	873910.	0. 55175639	5. 47361880
4 62157018	92 <b>9220</b> . 1	0. 49316280	5. 46385318
4. 65085598	<b>784530</b> .	0. 51269400	5. 47361880
4. 71922513	1039830.	0. 51269400	5. 48338435
4.83885474	1075130.	0. 59326019	5. 43455637
4.89500701	1150440.	0. 58105319	5. 46873599
4. 94627632	1205750.	0. 54179080	5. 47361980
5. 03172539	1261050.	0. 51269400	5. 50779834
5. 03172537	1314360.	0.52245959	5. 47361980
5. 02928398	1371550.	0. 50292839	5. 44432200
5. 09520180	1426970.	0. 49316290	5. 45408762
5.14158837	1482280.	0. 55175639	5. 47361890
5, 12449860	1537590.	0. 54199090	5. 43455637
5. 17088 <b>517</b>	1592890.	0. 48339720	5. 47361880
5. 19285783	1548200.	0.49315280	5. 43455637
5. 1855 <b>3361</b>	1703510.	0. 51757679	5. 43455637
5, 21238900	175882 <b>0</b> .	0.53222519	5. 41502520
5, 24168580	1814120.	0. 50292839	5. 38572832
5. 1928576 <b>3</b>	1859420.	0.53222519	5. 41502520
5, 21971322	1924730.	0.52734240	5. 45408762
5, 29733800	1930050.	0.49316280	5. 43455537
5. 26121698	2035360.	0.48927999	5, 37596277
5, 25145135	2070660.	0. 50292839	5. 39549395
5, 32957420	2145950.	0.50781119	5. 4 <b>2</b> 9 <i>6</i> 7364

## TABLE 2 Calculation of Thermal Diffusivity Values from Experimental Data

FLASH. FT DATE: 7/29/71

### OKLA. STATE UNIV. COATING AIR 230

	VALUE	TIME (SEC)
BASELINE:	0. 51312470	0. 48661017
HALFMAXI:	2. 9256623 <b>9</b>	0. 47707939
MAXIMUM:	5. 31561374	0.40919011

ALPH <b>A</b>	PER	VALUE	Time(SEC)
0.00315968	10.0	0. 99337363	0. 22891539
0. 0032 <b>0</b> 30 <b>0</b>	20. 0	1. 47362291	0. 28780382
0.00321028	25. O	1. 7137467B	0. 31602185
0. 0032 <b>0497</b>	30. O	1. 95387184	0.34552216
0.00321118	33. <b>3</b>	2. 11395442	0. 36448961
0.00320276	40. O	2. 43412017	0. 40638661
0. 00319483	50. <b>0</b>	2. 91436910	0. 47528982
0.00318505	60. <b>0</b>	3. 39461803	0. 55730617
0.00317127	66. <b>7</b>	3.71478438	0. 62469685
0.00310430	70. O	3. 8748559 <b>5</b>	0. 67626202
0.00309831	75. 0	4. 11499202	0.74320042
0.00312028	80. <b>0</b>	4. 35511648	0. 81770813
0 00300381	90 O	4 83534422	1 10555171

TABLE 3
Thermal Diffusivity Results

Sample (No.)	Temp.	Temp. (°F)	Diffusivity (cm <sup>2</sup> sec <sup>-1</sup> )
Steel	23.	73 <sup>-</sup>	0.183
Steel	93	199	0.163
Steel	204	399	0.137
Steel	315	5 <b>99</b>	0.113
Steel	426	799	0.094
Steel	537	999	0.078
Coating	23	73	0.00320
Coating	93	199	0.00305
Coating	204	39 <b>9</b>	0.00290
Coating	315	5 <b>99</b>	0.00274
Coating	426	799	0.00257
Coating	537	999	0.00241
Coating	426	799	0.00244
Coating	315	5 <b>99</b>	0.00251
Coating	205	399	0.00258
Coating	93	199	0.00273
Coating	23	73	0.00288

TABLE 4
Specific Heat Results

Temp.	Temp.	Coa	ting	Steel	
(°K)	(°C)	Run 1	Run 2		
350	77	0.51905	0,52145	0.47724	
375	102	0.53324	0.54027	0.48175	
400	127	0.5435 <b>6</b>	0.54995	0.49227	
425	1 <b>52</b>	0.55271	0.56119	0.50173	
450	177	0.5 <b>6190</b>	0.57115	0.50846	
475	202	0.56759	0.57716	0.51875	
500	227	0.57740	0.58447	0.52755	
5 <b>25</b>	<b>252</b>	0.58942	0.59532	0.53683	
550	277	0.60218	0.5987 <b>3</b>	0.545 <b>04</b>	
575	30 <b>2</b>	0.61699	0.601 <b>42</b>	0.55349	
600	<b>327</b>	0.63429	0.60287	0.56312	
625	35 <b>2</b>	0.65684	0.60469	0.57390	
650	377	0.68326	0.60510	0.58512	
675	402	0.71580	0.60443	0.59739	
700	427	0.75878	0.60494	0.60973	
725	<b>452</b>	0.81170	0.60692	0.62316	
750	477	0.85 <b>459</b>	0.60988	0.63734	
775	5 <b>02</b>	0.86087	0.61402	0.65170	
800	5 <b>27</b>	0.86361	0.62104	0.66687	
825	5 <b>52</b>	0.85323	0.63070	0.683 <b>09</b>	
8 <b>50</b>	57 <b>7</b>	0.80381	0.64010	0.70189	
875	<b>602</b>	0.75636	0.64876	0.72623	
900	627	0.72906	0.65818	0.75374	
<b>92</b> 5	652	0.71783	0.66983	0.78855	

TABLE 5

Thermal Conductivity Results

Temp.	73	199	399	666	799	599	399	199	73
Conductivity (BTU hr-1ft-1F-1)	.405	.430	. 438	.400	. 392	. 402	.397	. 389	. 364
Conductivity (W cm <sup>-1</sup> K <sup>-1</sup> )	0,00708	0,00752	0.00766	0.00699	0,00686	0,00703	0,00695	0.00680	0,00637
Diffusivity (cm² sec <sup>-1</sup> )	0.00320	0,00305	0.00290	0.00241	0.00244	0,00251	0.00258	0,00273	0.00288
Specific Heat (W sec gm <sup>-1</sup> K <sup>-1</sup> )	0.476	0.530	0.568	0.624	0.605	0.602	0.579	0.536	0.476
Density (gm cm <sup>-3</sup> )	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65	4.65
Temp.	23	93	<b>2</b> 0 <b>4</b>	537	426	315	205	93	23

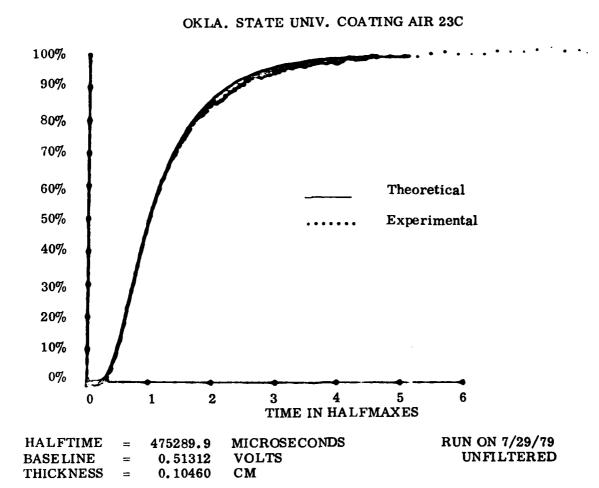
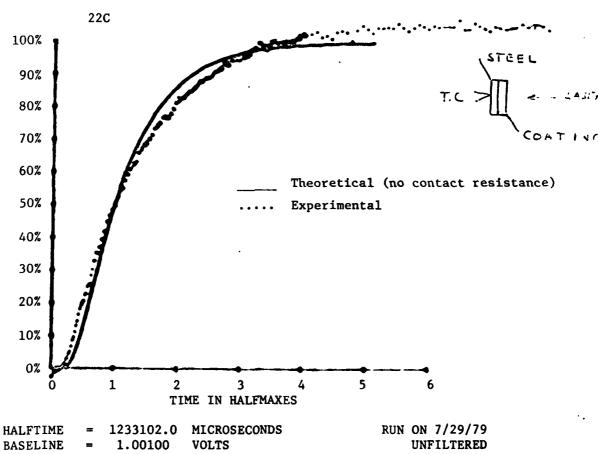


Figure 1. Comparison of Experimental

Rise Curve with Theoretical Model



BASELINE 0.15113 CM THICKNESS

Figure 2. Rise Curve with Contact Resistance Between Layers

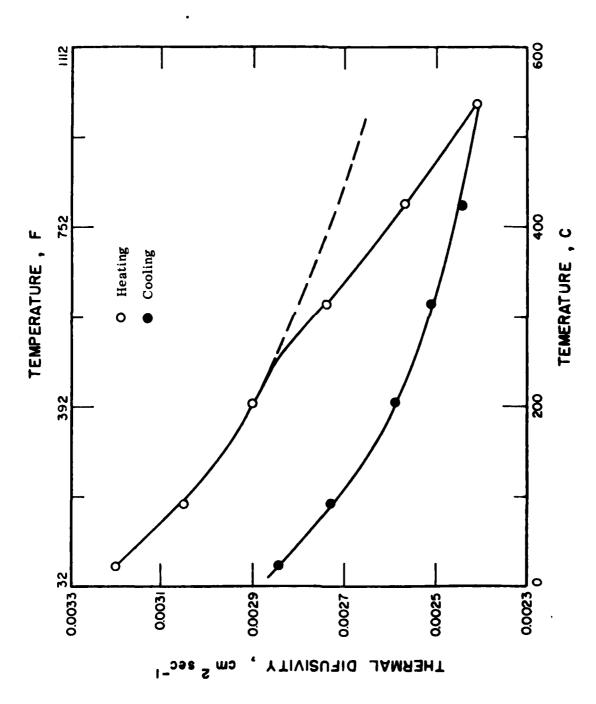


Figure 3. Thermal Diffusivity Results

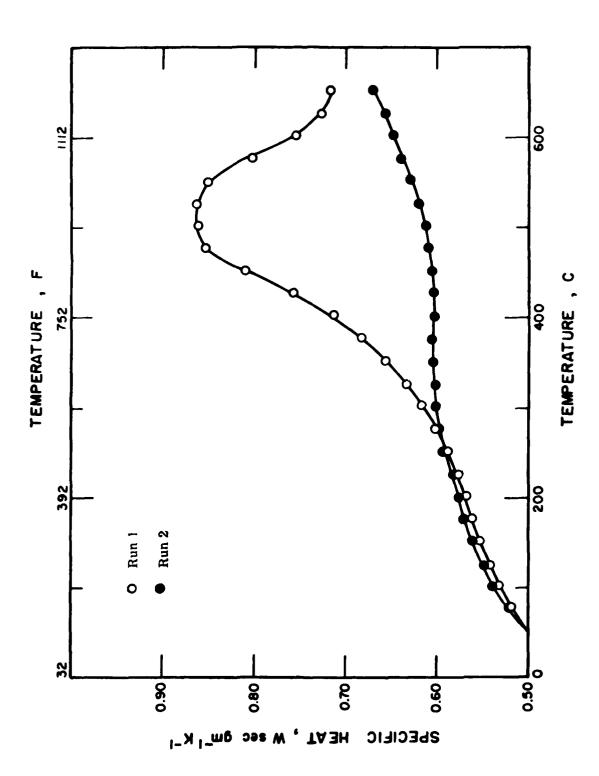


Figure 4. Specific Heat Results

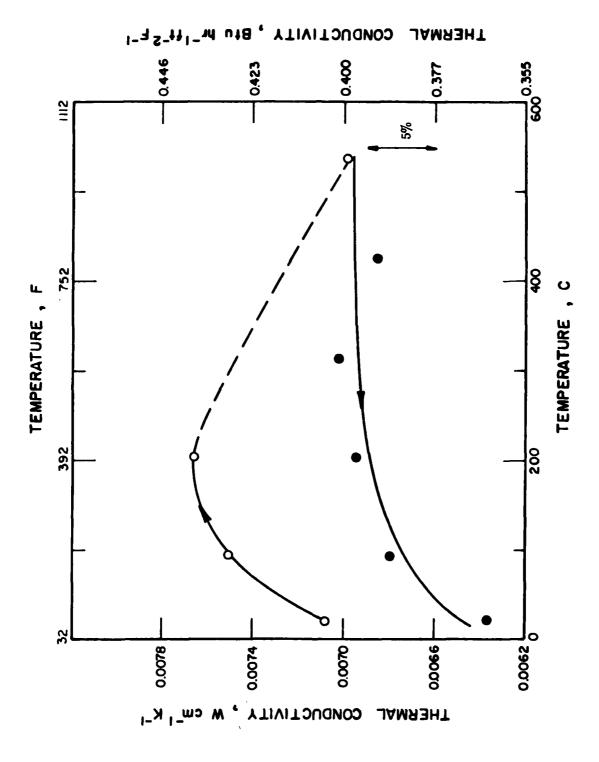


Figure 5. Thermal Conductivity Results

# DATE ILME